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AFML-TR-71-258

MANUFACTURING METHODS FOR SURFACE INTEGRITY OF MACHINED STRUCTURAL COMPONENTS

William P. Koster
et al
Metcut Research Associates Inc.

TECHNICAL REPORT AFML-TR-71-258
April 1972

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Air Force Materials Laboratory
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Wright-Patterson Air Force Base, Ohio

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FOREWORD

This final technical report covers all work under Contract F33615-70-C-1589 performed from 15 July 1970 to 15 October 1971. The report was released by the authors in January 1972.

This contract with Metcut Research Associates Inc., Cincinnati, Ohio, was initiated under Manufacturing Methods Project 721-0, "Surface Integrity of Machined Structural Components," and was accomplished under the technical direction of Captain Raymond H. Coe, Jr. of the Materials Processing Branch, Manufacturing Technology Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio.

Dr. William P. Koster, Director of Metallurgical Engineering at Metcut, was the engineer in charge. Others at Metcut who participated in this program were: Dr. Michael Field, John B. Kohls, Luciano R. Gatto, and Louis J. Fritz, who served as the manager of the experimental effort. This project was given the Metcut Internal Number 970-15000.

Metcut was assisted in this program by two subcontractors: The Boeing Company/Commercial Airplane Division, Seattle, Washington, under the direction of Birger Anderson and Clive Carter and the General Electric Company/Aircraft Engine Group, Evendale, Ohio, under the direction of Guy Bellows and Dr. Richard Johnson.

This project has been accomplished as a part of the Air Force Manufacturing Methods Program, the primary objective of which is to develop, on a timely basis, manufacturing processes, techniques and equipment for use in economical production of USAF materials and components.

Your comments are solicited on the potential utilization of the information contained herein as applied to your present or future production programs. Suggestions concerning additional manufacturing methods development required on this or other subjects will be appreciated.

This technical report has been reviewed and is approved.

Henry A. Johnson

HENRY A. JOHNSON
Chief, Materials Processing Branch
Manufacturing Technology Division
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ABSTRACT

A surface integrity evaluation of several iron, titanium and nickel base structural alloys has been completed. Materials investigated include AISI 4340, 4340 Modified, Grade 300 Maraging Steel, Ti-6Al-4V, Ti-6Al-6V-2Sn, Ti-6Al-2Sn-4Zr-2Mo, Inconel 718, AF 95, AF2-1DA, and Rene' 80. For the most part, these alloys were quenched and tempered or solution treated and aged, as appropriate, to put them into the high strength condition typically used for structural purposes.

Various grinding procedures caused the largest variation in surface integrity response. Fatigue strengths associated with gentle versus abusive grinding for Ti-6Al-6V-2Sn were 68 versus 10 ksi. Nickel alloys also showed large variations such as 70 versus 20 ksi in the case of gentle versus abusive grinding applied to AF2-1DA.

Hand sanding as a machining condition exhibited fatigue strengths ranging from 85 to 100 percent of those produced by gentle grinding on the same material. On steels, little or no fatigue difference was observed between gentle and abusive hand sanding. In the case of Ti-6Al-4V, however, abusive hand sanding caused a marked fatigue depression compared to gentle hand sanding, 30 versus 57 ksi.

End milling performed under gentle conditions with sharp tools resulted in alloy fatigue strengths generally equal to or greater than those exhibited by gently ground surfaces. Exceptions were in the case of 4340 and 4340 modified where fatigue strength in milling was 15 to 50 percent lower than that produced by gentle grinding. Traces of untempered and overtempered martensite are blamed for this fatigue depression. In general, abusive peripheral cutting exhibited lower fatigue strengths than gentle peripheral cutting. Variations in end cutting, however, had little affect on fatigue response.

Both EDM and ECM exhibited distinctive fatigue strengths characteristic of the alloy/process combination which were generally lower than those produced by gentle grinding. With minor exceptions, variations in both EDM and ECM process conditions had little affect on the fatigue behavior characteristic of each process.

Guidelines for processing of aerospace hardware in such a way as to assure good surface integrity have been developed and presented in this report. Control of cutting tool sharpness as well as proper selection of processing parameters are prime requirements.

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LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

TABLES OF DATA

TABLES OF DATA (cont.)

LIST OF ABBREVIATIONS USED IN THIS REPORT

AA	Arithmetic Average (Surface Roughness Height)
CHM	Chemical Machining
ECM	Electrochemical Machining
EDM	Electrical Discharge Machining
ELP	Electropolishing
UTM	Untempered Martensite
OTM	Overtempered Martensite

1. INTRODUCTION

During the past decade, there has been continuous activity in the development of high strength, corrosion resistant materials suitable for a wide variety of aerospace applications. Interest has ranged from development of very high strength steels suitable for structural purposes at temperatures near ambient levels to refractory and semi-refractory alloys usable in excess of 2000°F for space shuttle applications. Between these extremes, considerable attention has also been directed at titanium alloy development for the 500-1000°F region and at stainless steels/nickel alloys for the range of 1000-2000°F.

Dynamic loading is a limiting factor in the design of many engineering structures in all types of applications. Wherever dynamic loading is involved, operating stresses are frequently limited by the fatigue characteristics of the structural materials to be used. Service histories and failure analyses of dynamic components illustrate clearly that fatigue failures often nucleate at the surface of a component. It may thus be inferred that fatigue behavior is sensitive to surface condition. In considering stress corrosion resistance, here again it is recognized that the surface condition of a component is a primary factor in determining susceptibility to attack and subsequent failure. In summary, both fatigue and stress corrosion resistance are important materials properties which are highly surface oriented. Whenever these qualities are important to the performance of a structure, much attention should be paid to the surface characteristics of components.

Modern metal removal methods, both conventional and those which are electrically assisted, have been revised to more efficiently process the higher strength and high temperature alloys which have evolved in recent years. The newer high performance materials are generally found to be inherently "more difficult" to machine. At the same time, advanced designs have necessitated the requirement of holding closer dimensional control of large surfaces, as well as in areas of more intricate and complex geometry. All of these conditions have intensified the problem of the quality of a machined surface, either in terms of its integrity per se or in terms of distortion resulting from stresses produced in machining.

Considering: 1) the nature of advanced materials offering improved capabilities, 2) the difficulty in machining and finishing these higher strength materials, and 3) the sensitivity to component surface condition inherent in many operational modes to which these parts will be subjected, the need for paying careful attention to the surfaces of finished hardware is brought

critically into focus. In machining any component, it is necessary to satisfy the surface quality or surface integrity requirements. Surface integrity has two distinct and important aspects. The first is surface topography which describes surface roughness and other features of the geometry of the surface. The second is the surface metallurgy of the layer produced in machining, including the effect of any alterations with respect to the base or matrix metal which may be present. This second solid state aspect is the prime, but not exclusive area of interest in this report.

In a previous USAF contract, F33615-68-C-1003, Metcut carried out an initial detailed investigation of various aspects of surface integrity on structural aerospace alloys. The present contract is, from an engineering point of view, an extension or continuation of the original effort. The primary purpose of the current program is to obtain overall surface integrity evaluations of additional alloys/material removal methods of current interest to the aerospace industry. The program has also investigated additional performance areas; namely, low cycle fatigue, and elevated or service temperature behavior to determine the extent to which surface integrity variables are significant under these conditions.

Metal removal variables studied included grinding, hand sanding, milling, turning (facing), drilling, electrical discharge machining (EDM), and electrochemical machining (ECM). In general terms, metal removal variables ranged from gentle or finishing conditions which normally accomplish removal at slow rates to abusive or roughing conditions which accomplish metal removal at high rates. From another view, the gentle (or finishing or standard) conditions were those intended or thought to produce little or no surface damage. The abusive conditions were selected to intentionally introduce damage to the surface to an extent which could logically be encountered in a production operation in the event that adequate controls were not applied. Low stress grinding of each material has been used throughout as the baseline condition to which other fatigue results are compared.

In addition, a separate study was conducted in both grinding and milling to determine the effect of surface finish per se on surface integrity behavior.

This program was a collective effort of Metcut Research Associates Inc., General Electric Company/Evendale, and The Boeing Company/Seattle. Both General Electric and Boeing contributed experimental and engineering effort to this program on a subcontract basis.

Data presented in this report are for information only and may not be suitable for design of components or related materials engineering purposes.

2. OBJECT OF PROGRAM

The overall objectives of this program were as follows:

1) To develop specific surface integrity data on a number of currently important alloy/material removal combinations which would permit characterization of the various processes and parameters involved into one of three categories:

   - Those alloy/processing combinations which are sensitive to processing parameters, hence, exhibit a need for adequate control and at the same time, offer potential for process optimization in terms of surface integrity, cost and productivity;

   - Those combinations which are relatively insensitive to processing parameters, hence providing potential for controlled cost reduction by allowing increased removal rates, rougher finishes, etc.;

   - Those processes which generally result in low surface integrity behavior. Alloy/process combinations of this group must subsequently be subjected to an appropriate post-processing operation if component surfaces are to be stressed to a significant level.

2) To determine the relative effect of surface finish on surface integrity behavior and to develop information on the potential of surface finish controls as a means of controlling surface integrity;

3) To establish the translatability of surface integrity data normally developed as high cycle fatigue data at room temperature into two other important engineering areas:

   - Material performance in the finite life or low cycle fatigue region;

   - Material performance at elevated temperatures approximating the service exposure range for the various alloys studied.

2. OBJECT OF PROGRAM (continued)

4) To provide for redefinition and refinement of guidelines previously developed (AFML-TR-70-11) to assist in the control and evaluation of surface integrity levels where necessary.

In carrying out this program, the following alloy/metal removal combinations were evaluated:

	Materials Removal Method						
Test Materials	Surface Grind	Hand Grind	Mill	Drill	Turn	ECM	EDM
Ferrous Alloys							
AISI 4340	X		X				
4340 Mod.	X	X	X	X		X	
Maraging Grade 300	X	X	X	X		X	
Titanium Alloys							
Ti-6Al-4V, Beta Forged	X		X				
Ti-6Al-6V-2Sn	X	X	X			X	
Ti-6Al-2Sn-4Zr-2Mo	X		X				
Nickel Base Alloys							
Inconel 718	X				X	X	
AF 95	X				X	X	X
AF2-1DA	X					X	X
Rene' 80	X					X	X

The conclusions and guidelines contained in Sections 3 and 4 of this report are based not only on the experimental data developed in the current contract, but also on that obtained in the previous surface integrity effort (F33615-68-C-1003, AFML-TR-70-11). The bar graphs shown in Section 6 also summarize the data produced from both contracts. The individual sections describing the results of each alloy/metal removal combination contained in Section 6, however, cover only that data generated in the present contract. Likewise, data tables I through XXVIII are confined to information developed under the present contract.

3. CONCLUSIONS

The conclusions presented in this report are an integration of the information produced under the subject contract with that previously developed under F33615-68-C-1003. A very large quantity of data is involved. The contents of this section present an overall view of the surface integrity behavior characteristic of the various alloys and metal removal processes that have been studied. Detailed conclusions interpreting the response of particular materials to various surface integrity situations are contained in the data summaries for each alloy, Section 6.

3.1 Surface Grinding

Variations in surface grinding procedure exhibited the greatest potential for causing large variations in surface integrity in all of the alloys studied to date. Abusive grinding and also conventional grinding always cause significant depressions in fatigue strength when compared to gentle or low stress grinding. The greatest range of properties exhibited was in the case of Ti-6Al-2Sn-4Zr-2Mo in which the high cycle fatigue strengths resulting from gentle versus abusive grinding were 68 versus 10 ksi.

A summary of the high cycle fatigue response at room temperature for all of the alloys studied is shown in Figure 1. A review of these bar graphs will indicate that the ferrous alloys, 4340, 4340 modified, and the maraging steel, suffer a 20 to 50 percent loss in fatigue strength due to conventional and abusive grinding as compared to gentle grinding. The titanium alloys and the nickel base alloys, comprising the balance of the materials in Figure 1, are more drastically affected by conventional and abusive grinding. Losses as high as 60 to 80 percent are indicated. It is evident, however, that all of these materials can be successfully ground and with a resulting high level surface integrity providing that proper procedures are employed and that adequate controls are enforced.

This wide variation in response indicates a high sensitivity to grinding parameters. Since surface integrity behavior does vary so widely with grinding conditions, there is latitude for optimizing the grinding process for various materials to satisfy both surface integrity requirements and also production economics.

3.2 Hand Sanding

Hand sanding under both the belt and disc conditions which have been studied gives evidence of being only moderately sensitive to processing parameters. As may be seen in Figure 2, which summarizes available hand sanding surface integrity data, fatigue strengths are lower than those exhibited by gentle grinding, although the separation is not large. The greatest difference observed was in the case of maraging steel, where endurance limits associated with hand sanding versus gentle grinding were 85 versus 105 ksi. It is not intended to suggest that these differences are unimportant. Conversely, hand grinding when abusively done, does not appear to have the potential for causing damage of the magnitude which can be caused by surface sanding should abusive situations develop.

An exception to this would have to be made in the case of hand belt sanding of Ti-6Al-4V in the beta rolled condition. In this situation, the fatigue strength associated with abusive sanding was markedly lower than that resulting from gentle hand sanding, 30 versus 57 ksi.

It must be pointed out in considering this data that the information was developed for hand sanding as a finishing process applied over a test coupon which had been previously finished by low stress or gentle grinding. Data, therefore, is characteristic of the hand sanding process itself and is not a measure of the corrective ability of hand sanding as applied over a surface containing a detrimental or abusive condition. The merit of hand sanding as a post-processing procedure in overcoming adverse surface integrity situations is not implied by this data. In practical terms, hand sanding may not be generally applicable as a corrective procedure because of its limits in removing adequate quantities of metal especially on the harder, higher strength alloys.

An added point of caution is in order. While the sanding conditions evaluated show only moderately detrimental effects under some abusive conditions, this provides no assurance the greater damage would not be produced by other, still more abusive hand sanding practice.

3.3 End Milling

Abusive peripheral end milling has been shown to be detrimental in surface integrity. This data, however, as shown in Figure 3, is limited to titanium alloys. Notice also that gentle peripheral end milling provides somewhat higher fatigue strengths than gentle grinding again confined to titanium alloys.

In the case of end milling-end cutting, Ti-6Al-4V and the maraging steel both exhibit fatigue strengths at least as good as those provided by gentle grinding. The martensitic alloys, however, AISI 4340 and 4340 modified, both show significant depressions in fatigue strength under all milling conditions when compared to low stress grinding. This reaction of the 4340 alloys is probably associated with small amounts of untempered/overtempered martensite on the milled surfaces.

Surface integrity aspects of end milling must be considered in cutting all alloys. In processing martensitic steels such as 4340, some type of post-processing will usually be needed if maximum fatigue strength is required, regardless of milling conditions. In working with other alloys, maintenance of cutter sharpness is a prime control of surface integrity, especially in peripheral cutting. End cutting under abusive conditions, i. e., using dull cutters, does not appear to be detrimental. As a practical matter, however, most end milling operations produce surfaces both end cut and peripherally cut, hence the need to control cutter sharpness.

3.4 EDM

Electrical discharge machining has consistently demonstrated the characteristic of producing relatively low fatigue strengths on all materials which have been evaluated in this program. Typically, EDM fatigue strengths are less than half of those exhibited by gentle grinding. Data available is summarized in Figure 4. It may also be seen from reviewing this figure, that differences in processing parameters over the roughing-finishing range studied have little or no effect on the low level of surface integrity behavior. It appears reasonable to conclude that a surface produced by EDM always will require some type of a suitable post-processing procedure to remove or restore the surface layer in those situations where significant stresses are to be imposed on the part during service.

3.5 ECM

Electro-chemical machining on all of the alloys studied to date has exhibited a characteristic intermediate fatigue strength or surface integrity level. Like EDM, variations in the ECM process generally have little effect on the resulting fatigue strength level. An exception to this is in the case of Ti-6Al-6V-2Sn, where standard versus off-standard ECM resulted in fatigue strengths of 72 versus 47 ksi. Available data on fatigue behavior as a function of ECM processing are shown in Figure 5.

In relative terms, the surface integrity level resulting from ECM is approximately 10 to 25 percent lower than that exhibited by gentle grinding on the same material. Again, this comparison may be easily made in Figure 5.

3.6 Surface Finish

Surface finish studies, specifically developed to explore the relationship between the microinch finish of a surface and its characteristic fatigue strength were run on the following alloy/process combinations: 4340 steel/grinding, Inconel 718/turning, and Ti-6Al-6V-2Sn/end milling. The data obtained show a variation in fatigue strength of ± 7 percent (100 to 117 ksi) in the case of gentle longitudinal grinding applied to the 4340 steel over a surface finish range of 8 to 127 AA. In the case of gentle transverse grinding, the range of fatigue strength increased to ± 17 percent (85 to 120 ksi). In both cases, the poorest surface finish was associated with the lowest fatigue strength level. In the case of abusive grinding over a similar range of surfaces, the fatigue strengths were all substantially reduced and in fact were all the same (65 ksi), regardless of surface finish. As far as grinding on steel is concerned, it may be well to conclude that surface finish does have a moderate effect on fatigue behavior, but that the introduction of grinding damage as produced by abusive grinding has a larger (and detrimental) effect on fatigue behavior.

Fatigue studies on turned Inconel 718 over the range of 25 to 118 AA including the effects of both gentle and abusive turning showed no fatigue bias related to surface finish. All conditions studied produced identical endurance limits of 60 ksi. Similar comments are applicable to milling on Ti-6Al-6V-2Sn where surface finishes in gentle end milling ranging from 13 to 125 AA all exhibited an endurance limit of 82 ksi.

3.6 Surface Finish (continued)

A summary of this work is detailed in Section 6.11 of this report. As an overall conclusion based on the data available, it is evident that while surface finish may, in some cases, give an indication of surface integrity behavior, this criterion by itself is insufficient to determine or control quality of a machined surface insofar as its integrity is concerned.

3.7 Post Treatments

Shot peening has demonstrated its effectiveness in elevating fatigue strengths significantly on each alloy evaluated. As a post-processing operation, peening has been shown effective in overcoming detrimental effects of abusive grinding and the relatively low levels of fatigue associated with EDM. Shot peening is also effective in raising the fatigue strength exhibited by ECM. Considering any one alloy, peening generally has shown the ability of raising fatigue strengths resulting from various processing techniques approximately to the level exhibited by low stress grinding. The use of shot peening, however, cannot be considered as a panacea since it introduces a surface roughening and also fairly deep residual stress patterns which may lead to component distortion. Caution must also be exercised to avoid over-peening, which may cause a variety of damage to the surface. These aspects, therefore, provide limitations on its applications because of requirements for surface finish and dimensional accuracy.

3.8 Residual Stress

Numerous correlations have been made of the data presented in this report and elsewhere between residual stress profiles in machined surfaces and their corresponding fatigue strengths. There are a number of situations where a degree of correlation has been found. In general, if an alloy has been subjected to a metal removal process only, but has received no mechanical or thermal post treatment, then the peak stress level in the residual stress profile generally indicates an approximation of fatigue behavior. Such correlations break down, however, if phase transformations have occurred in the surface layer. Also, whenever mechanical post treatments such as peening are applied, or whenever post thermal treatments are involved, this approximation between residual stress and fatigue strength may no longer be applicable.

3.9 Surface Integrity Evaluation Methods

The standard data set consisting of studies of surface metallography, residual stress, and high cycle fatigue behavior is seen as the most practical,generally applicable method for evaluating a particular surface integrity situation. The standard data set evaluation includes a detailed study of surface layer microstructure, microhardness and residual stress profile, plus determination of the endurance limit in 10^7 fully reversed fatigue cycles using approximately eight fatigue specimens.

The introduction of low cycle fatigue evaluations in the present contract has been meaningful in that it has shown that materials are often influenced by, but generally less sensitive to surface integrity factors in the low cycle fatigue region than at the high cycle fatigue region. Actually, the ferrous alloys are slightly less sensitive in the high than in the low cycle region, while the titanium and nickel base alloys show little or no low cycle fatigue sensitivity to surface variables. Having determined that this was the case, it then serves for future work to confine general surface integrity evaluations to high cycle fatigue behavior.

Similarly, studies in both low and high cycle fatigue at elevated temperatures have shown that the effects observed at room temperature are, in most cases, carried over to the elevated temperature situation in roughly the same proportion. In other words, if an abusive/gentle situation causes a 30 percent drop in fatigue strength at room temperature, a similar difference will be observed in elevated temperature fatigue behavior, although the strength levels will usually be different. Having established that this relation does exist, again it is concluded that room temperature testing is sufficient to establish basic surface integrity behavior for new alloy/metal removal combinations being evaluated. It had been conjectured that elevated temperatures would "relax out" stress situations and possibly other factors which cause differing surface integrity response at room temperature, thus making elevated temperature behavior of materials relatively insensitive to surface integrity effects. This has been shown not to be the case. Surface integrity is definitely a factor in elevated temperature performance, but apparently standard evaluations of relative sensitivity can be conducted at room temperature.

In all of the work reported to date, low stress grinding has been considered as the surface integrity base line to which the performance of all other process and process variations is compared. It has been suggested that ECM or CHM might be used in place of low

3.9 Surface Integrity Evaluation Methods (continued)

stress grinding because of the purely stress free surface condition resulting from these processes. While it is recognized that gentle or low stress grinding does, in fact, produce low to moderate residual compressive stress in most surfaces, this process is felt to be the better base line choice because it is a practical, easily reproducible process that can be specified for a family of alloys in general terms and carried out in a large number of facilities. In contrast, proper ECM as well as CHM depends on the selection of appropriate electrolyte and other cutting parameters which are peculiar to each alloy being processed. This situation not only necessitates a development program to permit intelligent selection of parameters in order to work with a new alloy, but it also poses difficulties in providing a readily reproducible standard procedure. Furthermore, both ECM and CHM frequently cause a shallow softening of the alloy surface (.001 to .002" deep). This occurrence further mitigates against using either process as a baseline for comparison purposes.

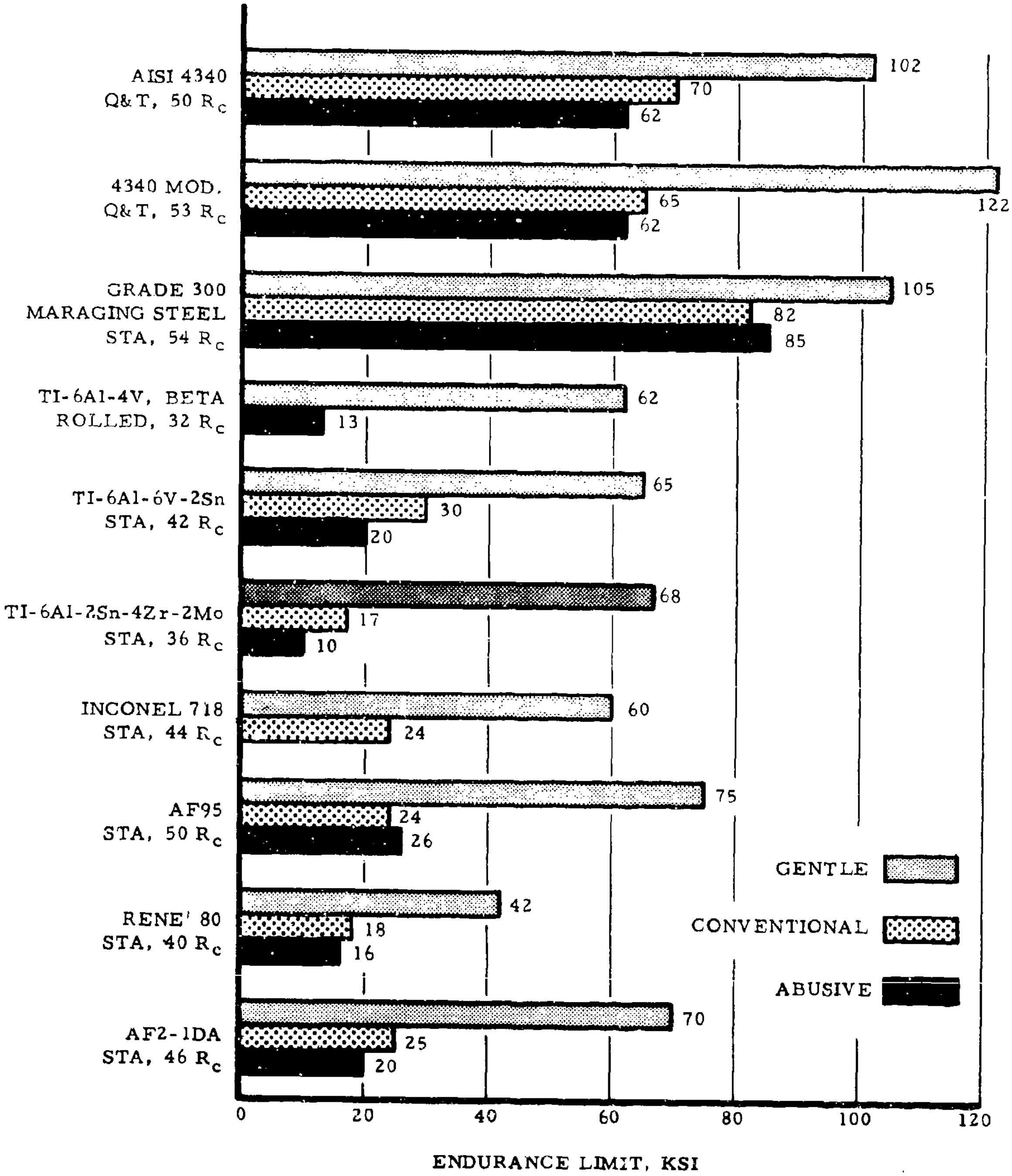


Figure 1
SUMMARY OF HIGH CYCLE FATIGUE RESPONSE: SURFACE GRINDING

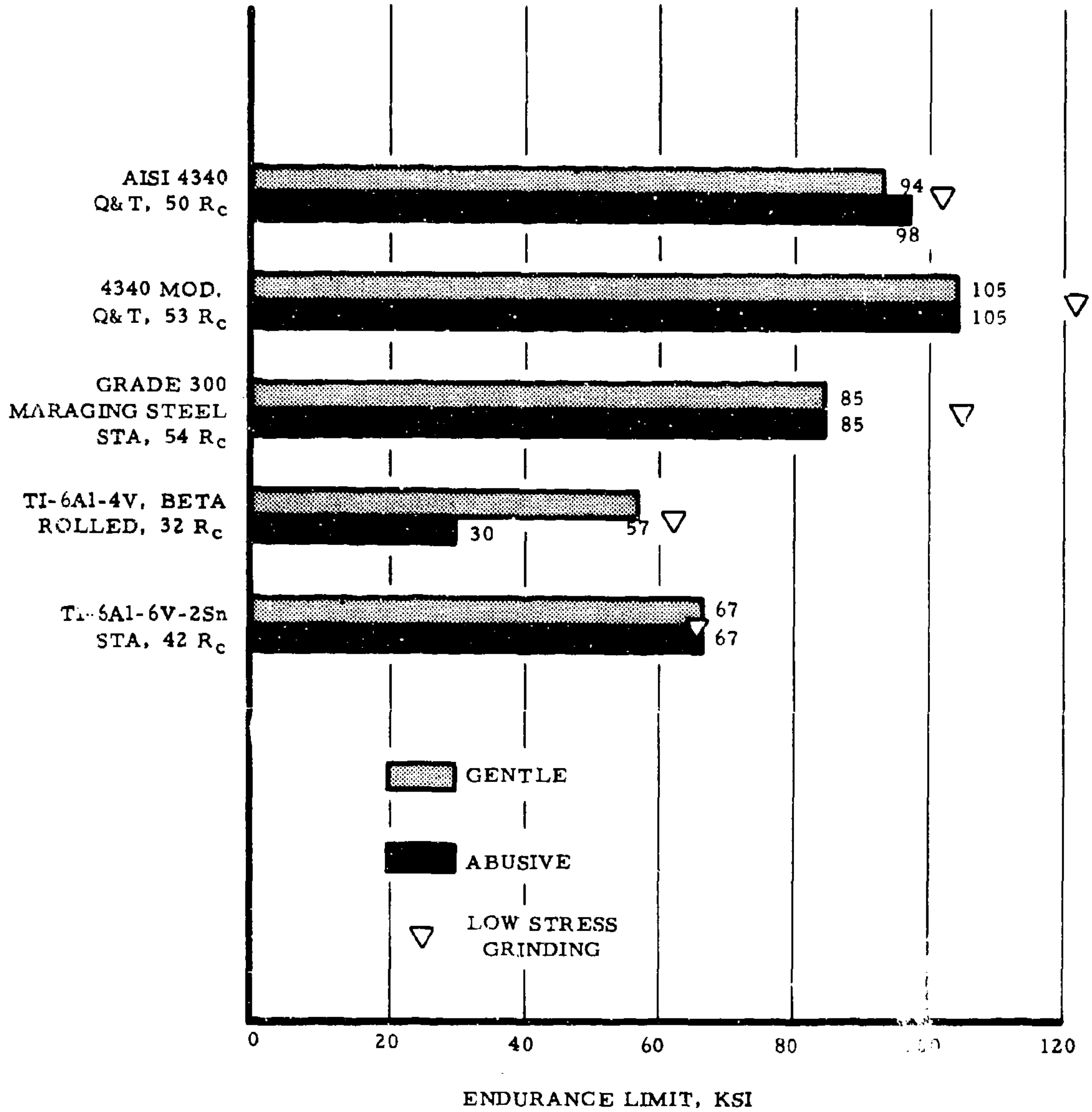


Figure 2

SUMMARY OF HIGH CYCLE FATIGUE RESPONSE: HAND SANDING

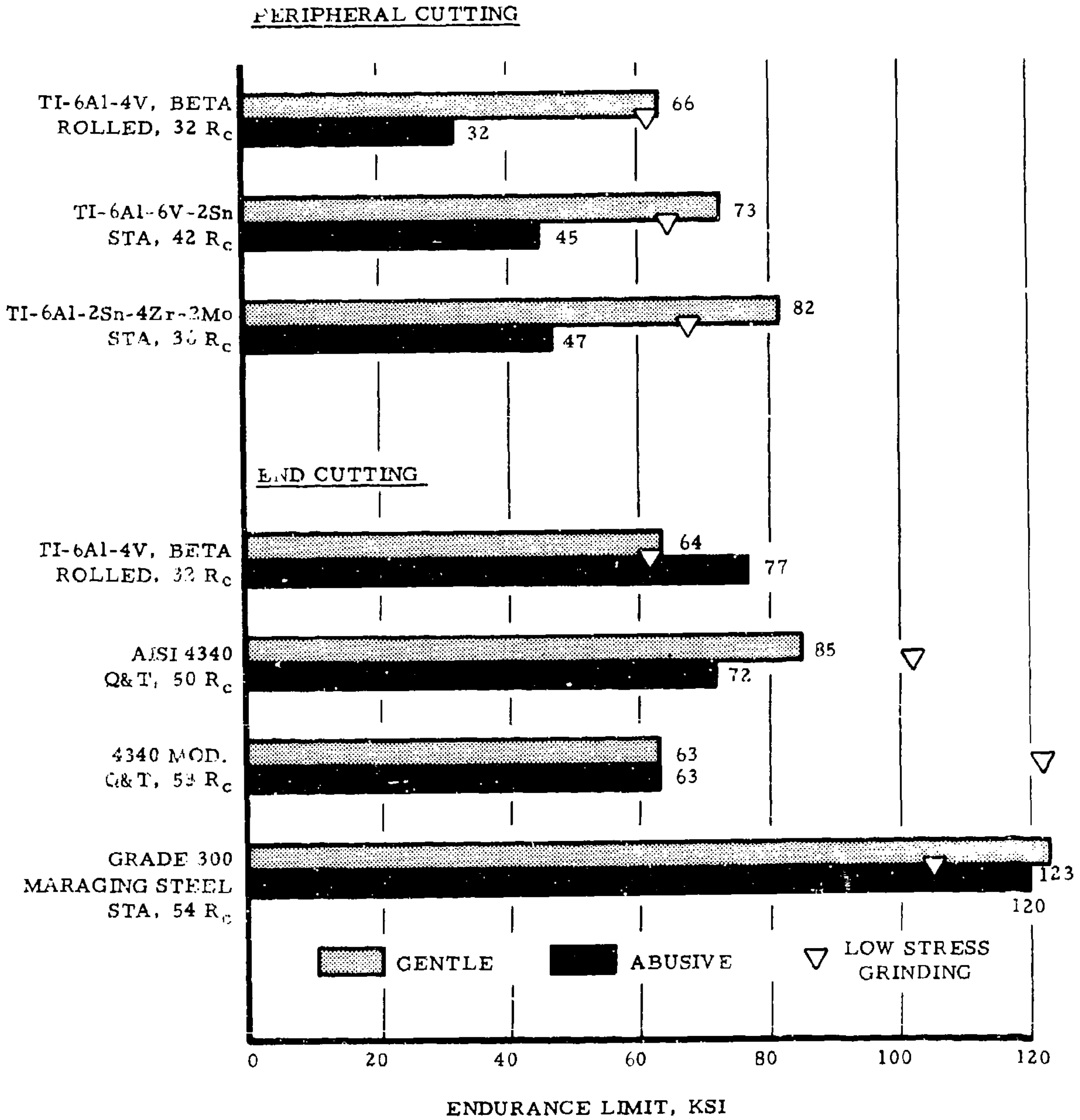


Figure 3
SUMMARY OF HIGH CYCLE FATIGUE RESPONSE: END MILLING

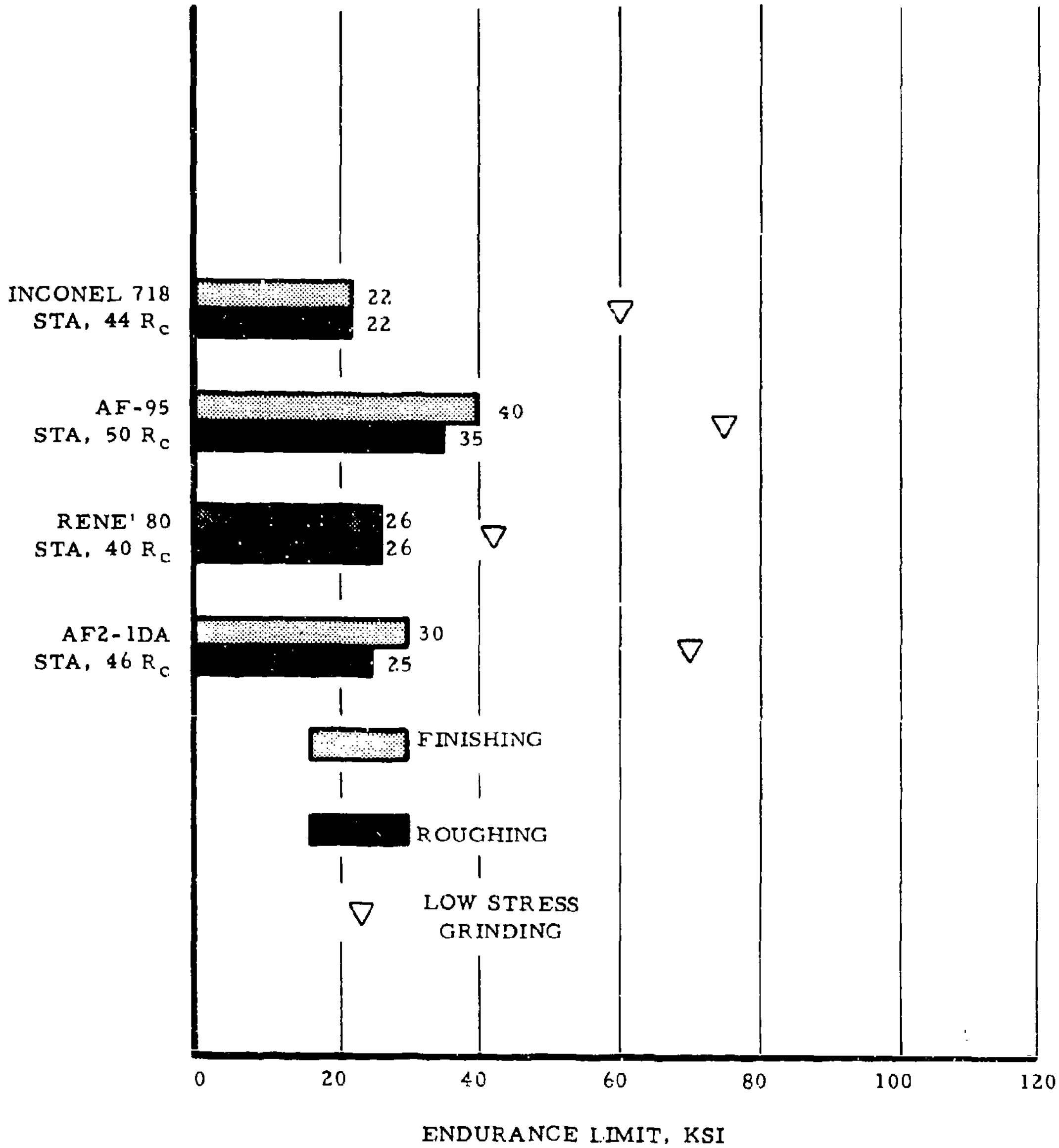


Figure 4
SUMMARY OF HIGH CYCLE FATIGUE RESPONSE: EDM

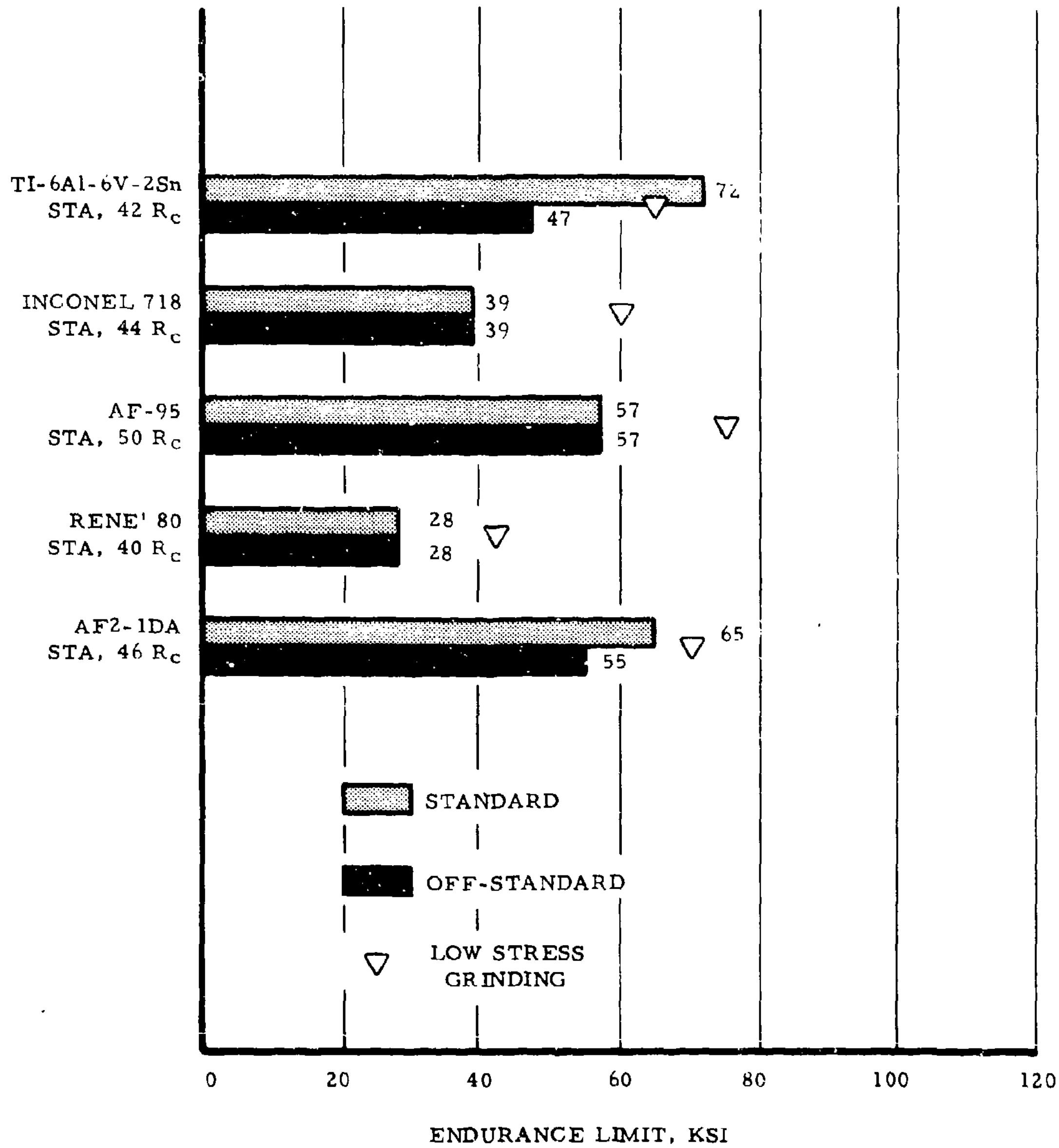


Figure 5
SUMMARY OF HIGH CYCLE FATIGUE RESPONSE: ECM

4. RECOMMENDATIONS: GUIDELINES FOR MATERIAL REMOVAL AND POST PROCESSING

Since 1951, the Manufacturing Technology Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio, has been sponsoring work on some aspects of surface integrity in conjunction with its machinability programs.(1)* Additionally, since 1968, the Manufacturing Technology Division has developed special programs devoted solely to surface integrity in order to meet the current and future critical manufacturing needs of the aerospace industry. Specific surface integrity data are reported in detail in Refs. 1 and 2 as well as in other sections of this report. While these and other efforts are developing significant quantities of specific surface integrity data, there is a continuing demand for surface integrity information on a very large number of combinations of materials, processes, and mechanical properties--a demand which cannot be satisfied entirely with hard data or specific service experience at the present time. In order to fulfill the immediate needs of designers and manufacturing engineers, an attempt is being made to develop Guidelines based upon current trends and analogies, even without having the benefit of controlled test data for specific combinations of materials, processes, and design parameters.

Previously, surface integrity guidelines for machining were presented and published as noted in Refs. 3 and 4. The following suggestions represent the latest updating.

PRECAUTIONS FOR USE OF SURFACE INTEGRITY GUIDELINES

Precaution 1

The Guidelines which follow are meant to serve as <u>general or starting recommendations only</u> for machining of structural components. Data and experience gathered to date indicate that these practices have led to increased surface integrity in some very important applications. However, the state of knowledge of surface alterations at this time is such that general recommendations are not always applicable for all specific surface integrity situations. For highly critical parts, it is mandatory to make individual specific evaluations. A suggested detailed

* References cited in these Guidelines are listed on page 427

Precaution 1 (continued)

and systematic approach is set forth in Guideline 39. It is also important to note that these Guidelines were formulated specifically based on experience with structural surfaces as opposed to mating or bearing surfaces. It appears, however, that many of these Guidelines are also applicable to mating surfaces of bearings, cams, gears, and other similar parts.

Precaution 2

It should be emphasized that surface integrity practices should not be specified unless the need exists. Therefore, when a requirement does exist for special controls in order to achieve surface integrity, one has no alternative but to recognize and accept any increased costs which might result from the need for employing more carefully controlled processing. In other words, a cost comparison of controlled processing versus uncontrolled processing when you have no choice is really meaningless or invalid. Process parameters which provide surface integrity should be applied selectively to critical parts or to critical areas of given parts to help minimize cost increases. Processing analyses made in the interest of achieving surface integrity can often lead to overall cost savings in production because a detailed study of surface requirements may make it possible to relax the finish and dimensional requirements in noncritical areas. Key indications of need for surface integrity control are:

1. Distortion in thin parts
2. Cracking in processing or in service
3. Short service life
4. Requirements for manufacturing parts using sensitive alloys such as high strength steels, nickel and cobalt base high temperature alloys, titanium alloys, beryllium, and refractory alloys
5. Manufacturing requirements calling for the use of material removal processes such as electrical discharge machining, laser beam machining, and rough conventional machining and grinding operations, which characteristically cause surface alterations
6. Exposure to operating conditions where a possibility exists that stress, temperature and environment may affect the properties of a material

Precaution 2 (continued)

7. Hazards to life
8. Possibility of high property loss
9. Requirements for designs which approach more complete utilization of material properties.

Precaution 3

These surface integrity guidelines are intended primarily for application to metal removal processes used for final surface generation rather than for roughing cuts. It is important, however, to know the type and depth of surface alterations produced during roughing so that adequate provisions may be made for establishing surface integrity during finishing operations by removing damaged surface layers.

Precaution 4

It is important to recognize that the field of surface integrity is in a state of rapid development, and therefore even its terminology is in a state of flux. By definition, surface integrity is the unimpaired or enhanced surface condition which is developed in hardware by using controlled manufacturing processes. In the formulation of surface integrity parameters and guidelines, the intent is to apply the term surface integrity when special steps are being taken to control manufacturing processes for the generation of surfaces designed to meet severe stress or environmental conditions.

Terminology is also required to describe specifically the set of conditions or material removal parameters which are used to achieve surface integrity. Any type of material removal operation in which parameters are especially selected in order to achieve improved service performance is modified by terms such as low stress or gentle (for example, low stress grinding, gentle grinding, gentle milling, etc.). Removal parameters or conditions which are known to be damaging are often referred to as abusive (such as abusive grinding, abusive milling, etc.). In the surface integrity literature, data are frequently obtained under so-called conventional machining and grinding conditions. Removal parameters which are commonly used or generally accepted in industry are referred to as conventional. It should be pointed out that conventional machining and grinding practices sometimes lead to a lack of surface integrity. It should also be emphasized that, ultimately, abusive and gentle processing can only be differentiated by mechanical testing (fatigue, stress corrosion, etc.) and/or service performance.

1. Reduce Grinding Distortion and Surface Damage by Using Gentle or Low Stress Conditions during Finish Grinding

Conventional finish grinding practices should be replaced by gentle or low stress grinding procedures to minimize grinding distortion and to reduce the possibility of producing extensive surface metallurgical alterations and cracking. Some of the metallurgical alterations caused by abusive grinding do not produce cracking immediately, but they develop conditions leading to delayed cracking, which may occur later "on the shelf" or prematurely in service, thereby seriously complicating inspection practices. Low stress grinding in comparison with conventional practices employs softer grade grinding wheels, reduced grinding wheel speeds, reduced infeed rates, and chemically active cutting fluids. Low stress conditions should be used for removing the last .010 in.

Surface Grinding - Typical Gentle or Low Stress (a)-see notes next page

Grinding Parameters	Steels and Nickel Base High Temperature Alloys	Titanium
Wheel	A46HV	C60HV
Wheel Speed	2500 to 3000 ft./min.(b)	2000 to 3000 ft./min.(b)
Downfeed	.0002 to .0005 in./pass(c)	.0002 to .0005 in./pass(c)
Table Speed	40 to 100 ft./min.(d)	40 to 60 ft./min.(d)
Cross Feed	.040 to .050 in./pass	.040 to .050 in./pass
Grinding Fluid	Highly sulfurized oil	Potassium Nitrite (KNO_2) in water (1:20)

Traverse Cylindrical Grinding - Typical Gentle or Low Stress

Grinding Parameters	Steels and Nickel Base High Temperature Alloys	Titanium
Wheel	A60IV	C60HV
Wheel Speed	2500 to 3000 ft./min.(b)	2000 to 3000 ft./min.(b)
Infeed	.0002 to .0005 in./pass(c)	.0002 to .0005 in./pass(c)
Work Speed	70 to 100 ft./min.(d)	70 to 100 ft./min.(d)
Grinding Fluid	Highly sulfurized oil	Potassium Nitrite (KNO_2) in water (1:20)

Notes:

(a) For a wide variety of metals (including high strength steels, high temperature alloys, titanium and refractory alloys) gentle or low stress grinding practices develop low residual stresses at and near the surface.

(b) Gentle grinding requires wheel speeds lower than the conventional 6000 ft. /min. In order to apply low stress grinding, it would be preferable to have a variable speed grinder. Since most grinding machines do not have wheel speed control it is necessary to add a variable speed drive or make pulley modifications.

(c) Downfeeds or infeeds in the range of .0002 to .0005 in. /pass have been found satisfactory for steels, nickel base high temperature alloys, and titanium alloys. A typical feed schedule calls for removing the last .010 in. of stock as follows: remove .008 in. at .0005 in. /pass and remove the last .002 in. at .0002 in. /pass.

(d) Increased work speeds even above those indicated are considered to be advantageous toward improving surface integrity.

2. Modification of the Gentle or Low Stress Grinding Procedures Noted in Guideline 1 Should Not be Attempted Unless Service Experience or Testing Programs in the Shop and/or Laboratory Confirm that Compromises Can be Tolerated

For certain type parts made of sensitive alloys, no compromises should be permitted in the specification of low stress grinding parameters. Experience has shown that it is sometimes possible to relax low stress procedures in order to accommodate equipment limitations or to increase production rates. Below is an example of a set of grinding conditions (A), which produced scrap as a result of grinding cracks in the fir tree section of IN-100 turbine blades. Substitution of conditions (B) produced no cracks. The parameters listed in (B) are essentially low stress except for the infeed. Experience had indicated that in this instance an infeed as high as .002 in. could be tolerated.

An almost identical cracking problem was encountered in the production of cast 713C turbine blades. This problem was also solved by implementation of the recommendations shown in (B) below. Parts made of cast HS31 and cast WI-52 have also cracked in conventional grinding. Because of these experiences and because of the lack of other data, it is suggested that all cast nickel and cast cobalt base high temperature alloys be processed using gentle or low stress grinding conditions.

Grinding Parameters	A (Cracks)	B (No Cracks)
Wheel	38A100I8VBE	38A80I8VBE
Wheel Speed	5500 ft./min.	2800 ft./min.
Table Speed	20 ft./min.	20 ft./min.
Infeed/Pass	.004 in.	.002 in.
Fluid	Sulfochlorinated Oil	Highly Sulfurized Oil
Grinding Cycle	Rough: .060 in. at .004 in./pass, dress. Leave .100 in. side for finish operation. Finish: .012 in. from finish size (3 passes at .004 in./pass; 2 sparkout passes)	Dress: feed .060 in. at .002 in./pass; Dress: feed .060 in. at .002 in./pass; Dress: feed .010 in. at .002 in./pass to finish size.

3. <u>If Gentle or Low Stress Grinding is Required for Finish Grinding, then Conventional Grinding Can be Used to Within .010 In. of Finish Size, Provided the Materials being Ground are Not Sensitive to Cracking (See Guidelines 4 and 5)</u>

During <u>conventional grinding</u>, any metallurgically altered layer, including stresses, is usually confined to approximately .005 in. of the surface or less. This makes it possible to remove most of the stock by conventional practices and then finish grind by using low stress methods. However, crack detection tests should be made to see that conventional grinding of the material in question does not create cracks. Stock allowances of the order of .010 in. or greater if necessary are suggested to compensate for location inaccuracies in holding fixtures.

4. <u>Finish Grinding of Critical and or Highly Stressed Surfaces of Sensitive Alloys Exposed to High Service Stresses Should Be Performed Using Gentle or Low Stress Grinding Instead of Conventional Grinding</u>

A partial list of sensitive classes of alloys, including examples of specific alloys, follows:

High Strength Steels - Wrought

- 4340 or 4340 Mod. at 40-54 R_c
- 300M or D6ac at 56 R_c
- Maraging Steels
- HP 9-4-45

High Temperature Nickel and Cobalt Base Alloys - Wrought

Rene' 41	Rene' 80
Udimet 700	AF 95
Waspaloy	AF2-1DA
Inconel Alloy 718	

Titanium Alloys - Wrought

- 6Al-4V
- 5Al-2.5Sn
- 6Al-2Sn-4Zr-2Mo
- 6Al-6V-2Sn

Following are high cycle, room temperature fatigue data showing the adverse effect of abusive and of conventional grinding compared with gentle or low stress grinding for several classes of aerospace materials:

MATERIAL	ENDURANCE LIMIT (ksi) (10^7 cycles fully reversed bending - room temperature) Gentle or Low Stress Grinding	Conventional Grinding	Abusive Grinding
High Strength Steels			
4340 (Q&T, 50 R_c)	102	70	62
4340 Mod. (Q&T, 53 R_c)	122	65	62
18% Maraging Steel, 300 Grade (ST&A, 54 R_c)	105	82	85
High Temperature Nickel Base Alloys			
Inconel Alloy 718 (ST&A, 44 R_c)	60	24	--
AF 95 (ST&A, 50 R_c)	75	24	26
AF2-1DA (ST&A, 46 R_c)	70	25	20
Rene' 80 (ST&A, 40 R_c)	42	18	16
Titanium Alloys			
Ti-6Al-4V (Beta Rolled, 32 R_c)	62	--	13
Ti-6Al-6V-2Sn, (ST&A, 42 R_c)	65	30	20
Ti-6Al-2Sn-4Zr-2Mo (ST&A, 36 R_c)	68	17	10

When untempered martensite (UTM) or overtempered martensite (OTM) are present, fatigue strength reduction of martensitic steels due to abusive grinding has been determined to be approximately equal regardless of the quantity of UTM or OTM present. Traces of UTM or OTM as well as .004 in. deep layers were associated with the same fatigue strength reduction. Reduction of the endurance limit was found to be about 30-35 percent. For quenched and tempered steels, OTM is invariably produced under the UTM. Even if the UTM is removed by gentle grinding, the fatigue strength is still reduced 25-30 percent. This indicates that overtempered martensite is as important as untempered martensite in influencing fatigue strength.

5. Conventional Grinding Conditions Should Not be Employed for Either Roughing or Finishing Alloys which are Ultra-Sensitive to the Grinding Process

From experience, certain alloys have been found to crack easily during conventional grinding, thereby increasing the likelihood of having cracks created which are not eliminated by finish grinding. The high temperature nickel and cobalt base cast alloys (such as IN-100, 713C, MAR-M509, HS31, WI-52, Udimet 500, Udimet 700, Inconel Alloy 738, etc., in contrast with wrought nickel and cobalt base high temperature alloys noted in Guideline 4, are examples of alloys which should not be ground conventionally at all. See Guideline 2 for a specific case history involving cracking of a cast nickel base high temperature alloy. Metals and alloys which are brittle, such as beryllium and tungsten, tend to respond similarly.

6. Frequent Dressing of Grinding Wheels Can Reduce Surface Damage by Keeping Wheels Open and Sharp thus Helping to Reduce Temperatures at the Wheel-Workpiece Interface

Automatic dressing and wheel compensation contribute to the economic feasibility of frequent dressing. Crush dressing and diamond roll dressing can also be used to minimize the cost of frequent dressing.

7. Cutting Fluids, Properly Applied, Help Promote Surface Integrity

In order to get fluid to the wheel-workpiece interface, position the fluid nozzle as close to the wheel as possible. A general rule of thumb, regarding the quantity of fluid needed is to use at least two gallons of fluid per horsepower per minute.

8. Portable Hand Grinding and Off-Hand Grinding of Sensitive Alloys Should be Discouraged

The inherent lack of control has been responsible for creating many surface defects.

9. Abrasive Cutoff Requires Special Surface Integrity Considerations

Abrasive cutoff operations generally cause deeper surface layer alterations than grinding, sometimes as much as .100 in. Also, capability for minimizing damage from cutoff operations varies from plant to plant. Therefore, it is recommended when abrasive cutoff is used that steps should be taken to determine the extent of the disturbed layer and to make proper stock allowances for subsequent cleanup by suitable machining. Also, the entire cut surface should be examined because the temperatures generated are subject to extreme variation across the cut.

10. Controls for Hand Power Sanders Should be Maintained

Test data have shown that good fatigue results can be obtained for such alloys as 4340 at 50 R_c and Ti-6Al-4V provided controlled conditions are maintained. The conditions are:

a. Use a low belt speed (2000 surface ft./min. maximum, for example)
b. Use a flexible or resilient (rubber) support for sanding disks or belts
c. Use an abrasive grit, generally no coarser than 80, with coolant if feasible.

11. At Present, the Relatively New High Speed Grinding Processes Should Not be Used for Finishing of Highly Stressed Structural Parts Unless an Extended Data Set is Developed (See Guideline 39)

Presently, insufficient mechanical property data are available to justify the recommendation of high speed grinding for critical parts even though increased production rates are attainable. High speed grinding increases the difficulty of effective application of grinding fluid, especially on complex parts, thereby making it more difficult to avoid surface damage from overheating.

12. <u>Abrasive Processing and Especially Finish Grinding Must be Accomplished Under Strict Process Control when Employed for Manufacture of Aerospace Components</u>

Tests have shown that uncontrolled abusive as well as conventional grinding can substantially decrease the low and high cycle fatigue strength at room and elevated temperatures for titanium alloys, nickel base high temperature alloys and high strength steels. In addition to the room temperature high cycle fatigue data shown in Guideline 4, data have been developed for high cycle, elevated temperature and for low cycle fatigue . Tests or AF 95 show that at 1000°F the endurance limit (10^7 cycles) fully reversed bending is lowered from 98 ksi for gentle grinding to 48 ksi for abusive grinding. Low cycle fatigue properties are affected adversely by abusive grinding:

LOW CYCLE FATIGUE room temperature		Stress for Failure at 20,000 Cycles (ksi)
4340 (Q&T, 50 R_c)	Gentle Surface Grind	165
	Abusive Surface Grind	142
Ti-6Al-4V (Beta Rolled, 32 R_c)	Gentle Surface Grind	92
	Abusive Surface Grind	71
Inconel Alloy 718 (STA, 44 R_c)	Gentle Surface Grind	160
	Abusive Surface Grind	127
Rene' 80 (STA, 40 R_c)	Gentle Surface Grind	55
	Abusive Surface Grind	45

CHIP REMOVAL OPERATIONS

13. <u>Rigid, High Quality Machine Tools are Essential</u>

They must be designed with ranges of speeds and feeds necessary to meet surface integrity requirements. See Guideline 15 for comments on the need for selecting speeds and feeds which give long tool life.

14. Cutting Tools Should be Inspected Carefully Prior to Use

Cutting tools must be carefully ground, and the most right tool design should be employed. For example, stub length drills should be used instead of a jobber's length wherever possible. Cobalt or premium grade high speed steel should be used wherever carbide is not applicable so as to do everything possible to provide a low rate of tool wear. All tools should be inspected after grinding to insure that previous wear, chipping, galling, etc., have been corrected and meet tool specifications. After grinding, the cutting edges of all tools should be protected to prevent accidental damage in transit or handling. Tools should be double checked by the machine tool operator for obvious defects.

15. Sharp Tools Help Establish Surface Integrity in Turning and Milling

In chip removal operations as in grinding operations, it is important to produce a surface which has a minimum or preferably an absence of surface alterations; that is, the surface layer should be similar to the bulk material below the surface.

In turning and milling, there are at least two very important steps which will improve surface integrity. First, machining conditions should be selected which will give long tool life and good surface finish. Second, all machining should be done with sharp tools. Sharp tools minimize distortion and generally lead to better control during machining. The maximum flank wear in turning and milling should be limited to approximately .005-.008 in. A good rule of thumb is to remove the tool when the wearland becomes visible to the naked eye since a .005-.008 in. wearland is just barely visible to the naked eye. Dull tools develop high compressive stresses which cause distortion, and very often they produce tears and laps and also metallurgical alterations of the surface including untempered and overtempered martensite in steels. In turning of most alloys, carbide tools tend to have the lowest wear rate and at the same time make it possible to meet reasonable production rates. Throwaway carbide tools, in particular, should be used whenever possible. This will expedite rapid change of cutting edges whenever tool wear reaches its specified limit.

In order to determine machining conditions which will provide long tool life, it will be necessary to refer to tool life data for specific materials and material removal operations. References 6 through 9

supply data on tool materials, tool geometry, feeds, depths of cut, cutting fluids, etc., for the purpose of achieving long tool life. If tool life data are not available, a material closest in characteristics to the actual work material can be used for initial consideration of machining parameters. In addition, it is recommended that tool life data be studied carefully in order to develop the relationship between machining parameters and tool life. In this way, one can get an idea of the effect of changes in speeds, feeds, tool materials, etc., on tool life and be in a better position to decide on departures from the recommended machining parameters.

Any evidence of burning as a result of a tool or cutter breakdown should be reported to supervision. Care must be taken to remove sufficient stock after tool breakdown to completely remove the effects of the burning which may extend to as much as .005 in. to .010 in. of the machined surface.

There is a tendency for more surface damage to occur in the transient surface than on generated surfaces in turning and milling. Likewise, there is a tendency for more surface damage to occur when a long cutting edge produces the final surface. This situation usually exists when turning to a shoulder or when milling a radius into a component. Hence, when transient surfaces or formed surfaces of the above type become finished surfaces, special care must be exercised to avoid surface damage. The use of especially sharp cutters for finishing is desirable to minimize the alterations in this case. In turning, whenever possible a shoulder or large radius should be generated by a finishing tool rather than formed by the long cutting edge of a forming tool.

16. Sharp Drills Should be Used to Help Avoid Serious Surface Layer Alterations

Specified power speeds and feeds, as well as all other recommended drilling conditions, should be followed. Holes in highly stressed components should be free of tears, laps, untempered or overtempered martensite. To minimize defects, the wearland on drills should be limited to .005 in. to .008 in. Wherever possible, all hand feeding during drilling should be avoided. When drilling assemblies, a rigid machine tool or gantry type drill should be employed in preference to portable drilling equipment. Dwelling should also be avoided because it produces damage and may even friction-weld the drill to the workpiece. The operator should visually check the hole and drill after each operation.

If average or localized wear exceeds specifications, the drill should be replaced. If abnormal conditions develop in the hole, it should be marked and inspected thoroughly before assembly. Galling, torn surfaces, or discoloration due to overheating are causes for rejection. When a drill wears excessively or actually breaks in the drilling of sensitive alloys, the operator should notify appropriate personnel in order that remedial steps be taken. Accidents of this type indicate that proper machining conditions have not been selected and/or used properly. Coolant-fed drills may help minimize surface damage, but no supporting data are available.

17. Proper Drill Fixturing Assists in Minimizing Damage During Drilling

When drilling holes 1/4 in. or larger, a drill fixture or bushing should be used. Where accessibility permits, a drill backup should be used to minimize burring.

18. Finishing of Drilled Holes is Imperative

Entrance and exit of all holes should be carefully deburred and chamfered. All holes should be finished after drilling whenever possible to insure better surface finish and surface integrity. (See Guidelines 19, 20, and 21)

19. Special Precautions Should be Taken in Reaming of Holes in Sensitive Alloys

Since reaming often serves as a final hole finishing operation, all machining parameters must be controlled. Stock allowances must also be controlled. Power feeding of power driven machines should be employed for reaming of straight holes. On tapered holes (using power driven machines), hand feeding is permissible but power feeding is preferred. Hand reaming (using a tap wrench) of tapered holes may be permissible after power reaming. If hand reaming is performed, special attention should be placed on selection of tool material, reamer geometry, and accuracy in grinding the reamer. In addition, it may be advisable to provide for alignment of the reamer to insure accuracy during the hand reaming operation.

Double ream all straight holes 5/16 in. or larger with a minimum metal removal of 3/64 in. on diameter. On smaller holes, the minimum metal removal should be 1/64 in. on the diameter. The operator should

visually check the reamer for sharpness after each operation. At the first sign of chipping, localized wear or average flank wear beyond specification, the reamer should be replaced and the hole should be inspected. Also, regardless of hole and reamer condition, a maximum number of holes should be specified for reamer replacement. Each reamed hole should be carefully inspected for surface finish, galling, smearing, scratches, etc. Entrance and exit of all holes should be carefully deburred and chamfered.

20. Deburring and Chamfering Should be Used to Remove All Sharp Edges

Drilled and reamed holes should be countersunk or chamfered at the entrance and exit to remove the entire burr because sharp edges and burrs are common sources of component failure. To countersink, use power feed units if possible and use a countersink which completely avoids chattering. Generally, low spindle speeds are desirable. As for other operations, chamfering tools should be kept sharp.

The operator should visually inspect the tool after each cut, and it should be replaced if any visual evidence of wear is observed. The breaking of edges or radiusing may be done by abrasive deburring using a low speed, power hand drill. In chamfering of a part. a minimum of .010 in. chamfer is advisable. The break-edges and chamfers should be carefully examined for compliance with good surface finish requirements. This is especially important on the entrance and exit of holes where fatigue failures have a tendency to originate.

21. Honing is an Excellent Finishing Operation for Developing Surface Integrity

Honing is usually used only when finish requirements or tolerances are too close for practical use of other finishing operations such as reaming, grinding, etc. A multi-stone head is preferred; heads with steel shoes and/or steel wipers are not recommended. Honing produces less surface deformation and surface integrity damage than any other hole finishing process.

22. Boring May be Used as a Finish Machining Operation if Roughness is Within the Manufacturing Engineering Limits

In boring, extra precautions should be taken in preparation of the cutting edge to provide extremely fine surface finish. The tool wearland

in finish boring should be limited to .005 in. but often is far less than this in order to achieve the desired accuracy and surface finish.

ELECTRICAL, CHEMICAL, AND THERMAL MATERIAL REMOVAL PROCESSES

23. Whenever Electrical Discharge Machining (EDM) is Used in the Manufacture of Highly Stressed Structural Parts, the Heat Affected Layer which is Produced Should be Removed

The altered surface layer which is produced during EDM lowers fatigue strength of alloys significantly. The altered layer consists of a recast layer with or without cracks, some of which extend into the base metal, plus metallurgical alterations such as rehardened and tempered layers, intergranular precipitates, etc. Concern over the lowered fatigue strength is in reference to critical and/or highly stressed structures. In many tool and die applications, the altered layer has not caused problems and there have even been reports of improved die life. Generally, during roughing EDM, the layer showing microstructural changes, including a melted and resolidified layer, is less than .005 in. deep, while during finishing EDM it is less than .001 in. See Guideline 29 for suggested post-processing methods.

The detrimental effects of surface alterations caused by EDM are shown below in comparison with low stress grinding:

	ENDURANCE LIMIT (KSI) AT ROOM AND ELEVATED TEMPERATURES (10^7 cycles fully reversed bending)	
	Gentle or Low Stress Grinding	EDM (Finishing Conditions)
Inconel 718 (STA, 44 R_c)	60 (RT)	22 (RT)
AF 95 (STA, 50 R_c)	75 (RT) 98 (1000°F)	40 (RT) 50 (1000°F)
Rene' 80 (STA, 40 R_c)	42 (RT)	26 (RT)
AF2-1DA (STA, 46 R_c)	70 (RT)	30 (RT)

RT = Room Temperature

Shot peening of EDM surfaces restores fatigue properties based upon tests in this program. See Guideline 31.

24. Whenever Electrical Discharge Grinding (EDG) or Electrochemical Discharge Grinding (ECDG - sometimes referred to as ECDM) is Used in the Manufacture of Highly Stresses Parts, the Heat Affected Layer which is Produced Should be Removed

The removal conditions for EDG and ECDG essentially produce the same surface effects as EDM, however, the altered layers are usually shallower and frequently less than .001 in. deep.

25. Electrochemical Grinding (ECG) Should be Controlled Carefully in Order to Establish and Maintain Surface Integrity

The ECG process, using a metal bonded abrasive wheel as an electrode, should be controlled to avoid shorting. Also, since some metal is removed by the abrasive grains, it is possible to locally overheat parts just as in ordinary grinding. The surface effects of properly ground parts are very shallow and generally less than .001 in. It is desirable to maintain a full flow of electrolyte and a good balance between feed rate and electrolytic cutting rate so that mechanical removal is under 5 percent and preferably less than 1 percent of total as shown by only a few light scratches being present.

26. Surface Integrity Evaluations Should Be Made When Chemical (CHM) and Electrochemical (ECM) Processes are Used for Finishing Critical Parts

The fatigue strength of surfaces produced by controlled chemical and electrochemical processes has often been found to be lower than that produced by some of the more commonly used material removal processes. This is generally attributed to the unworked, stress-free surface produced by processes such as ECM, electrolytic polishing (ELP), and chemical machining (CHM). There is evidence that processes such as milling and polishing may sometimes provide beneficial fatigue resistance as a result of cold working. Therefore, when substituting ECM for other machining processes, it may be necessary to add post processing operations such as steel shot or glass bead peening or mechanical polishing. Some companies require peening of all electrochemically machined surfaces of critical and/or highly stressed structural parts. (See Guidelines 30 and 31.)

Gentle or abusive ECM of Inconel Alloy 718, for example, gave a fatigue strength of 39,000 psi as compared to 60,000 psi for low stress grinding. Electrolytic polishing of Inconel Alloy 718 gave a value of 42,000 psi, virtually no improvement over ECM. Additionally, surface integrity of CHM and ECM surfaces is lowered by intergranular attack (IGA), preferential solution of microconstitutents, erosion, and shorting. When shorting occurs, the high temperature arc melts and vaporizes a local spot. Below the spot, there are other microstructural changes which can also be detrimental. During ECM, parts should be fixtured in a way that will provide good electrical contact. Otherwise, there is a danger of localized overheating as a result of resistance heating. Cases have been observed where the damage in the form of discoloration is barely discernible on the surface. However, just below the surface the microstructure revealed the effects of extensive overheating including very large grain size. ECM, improperly applied, can also cause IGA and pitting as in the case of high strength aluminum alloys. Such defects are often responsible for stress corrosion and fatigue failures.

27. Special Cognizance Should be Taken of the Surface Softening that Occurs in CHM and ECM of Aerospace Materials

Microhardness studies on aerospace alloys (Reference 2) have shown that CHM and ECM produce a soft layer in a majority of the aerospace alloys. Hardness reductions for CHM and ECM range from 3 to 6 Rockwell "C" points to a depth of .001 in. for CHM and .002 in. for ECM. Shot peening or other suitable post processing should be used on such surfaces to restore mechanical properties.

28. Laser Beam Machining (LBM) Develops Surfaces Showing the Effects of Melting and Vaporization

Applications for LBM are not very common yet. Recently, however, LBM with oxygen assist has been investigated for cutting (instead of shearing) of various alloys including titanium. Also, LBM has been used for production of small holes. Wherever LBM is used in manufacturing highly stressed structural members, it should be remembered that in the application of this method the surface is subjected to melting and vaporization. Indications are that such surfaces should be removed. It becomes difficult, however, to apply secondary processing to parts containing very small diameter holes or narrow slots. As a first step, it is suggested that critical parts made by LBM be tested to see if surface alterations lower the critical mechanical properties.

POST PROCESSING

29. Cracks, Heat Affected and Other Detrimental Layers Created During Material Removal Processing Should be Removed from Critically Stressed Parts

By microstructural examination and microhardness testing, the depth of adversely altered layers and other defects can generally be established. Certain critical situations may require mechanical testing to be certain that no alterations have been produced which cannot be detected by microexamination. Secondary processes which are currently being used include:

a. Gentle conventional finish machining such as milling and reaming
b. Mechanical polishing
c. Sanding
d. Low stress grinding
e. Honing
f. Chemical milling plus peening
g. Electrochemical milling plus peening
h. Electropolishing plus peening
i. Heat treatment

30. Steel Shot and Glass Bead Peening as Well as Burnishing Can be Used to Improve Surface Integrity

A considerable number of studies, including those developed in Reference 2, confirm that fatigue life determined in laboratory tests and proven by field performance is measurably enhanced by peening. Laboratory tests have shown that shot peening is effective in substantially increasing high cycle and low cycle fatigue strength at both room and elevated temperatures for typical titanium alloys, high temperature alloys, and high strength steels regardless of the type of prior material removal processing. EDM and abusive grinding are two processes which are among the most detrimental to the alloy classes noted above. However, shot peening has been shown capable of making full restoration of low cycle and high cycle fatigue at room and elevated temperatures. Since the above comments are based upon laboratory tests, component evaluations are recommended. See Guideline 31. Peening, which puts the surface layer into compression and cold works the surface, must be performed under controlled conditions. Specifications for controlled peening should include

consideration of factors such as cleanliness and surface roughness of the part being machined; type, chemistry, geometry and hardness of the shot and its fluid carrier; peening time, intensity and coverage. Reports also indicate that peening improves resistance to corrosion and a large reduction in stress corrosion susceptibility. These are indications that cold working of drilled holes by burnishing is also beneficial as is roller burnishing of round and flat surfaces. Some reports contain precautions warning against overpeening in order to avoid fatigue damage and to reduce the possibility of masking flaws such as fine cracks.

31. Evaluate the Use of Controlled Shot Peening Practices to Restore Fatigue Life of Components Processed by Electrical, Chemical, and Thermal Removal Processes

Shot peening, based upon tests conducted in this study, has been shown to be extremely effective in improving the fatigue life of specimens processed by ECM, EDM, ELP. Component tests are recommended to confirm the results of the laboratory tests. Particular attention should be paid to evaluating the effect of environmental conditions such as elevated temperatures which might nullify the beneficial effects of shot peening. Examples are:

	ENDURANCE LIMIT (KSI) HIGH CYCLE FATIGUE (10^7 cycles fully reversed bending)
AF 95 (STA, 50 R_c)	
ECM	57
ECM + Peen	105
EDM	40
EDM + Peen	115
Low Stress or Gentle Grind	75
Inconel 718 (STA, 44 R_c)	
ECM	39
ECM + Peen	78
ELP	42
ELP + Peen	78
Low Stress or Gentle Grind	60

	ENDURANCE LIMIT (KSI) HIGH CYCLE FATIGUE (10^7 cycles fully reversed bending)
Ti-6Al-6V-2Sn (STA, 42 R_c)	
ECM	72
ECM + Peen	85
Low Stress or Gentle Grind	65

32. Post Heat Treatments Following Material Removal are of Limited Usefulness

Stress relief treatments used to soften hardened layers produced during grinding of steels do not restore the hardness of overtempered layers which are present immediately below the damaged surface layer. Also, heat treatment does not heal any cracks produced during material removal. Some companies have advised the use of tempering operations to relieve stresses after EDM of steels. Stresses may be relieved but fatigue properties are not improved sufficiently. Evidence has also been presented to show that annealing treatments following EDM on nickel base alloys such as Rene' 41, Inconel Alloy 625, Inconel Alloy 718 and Monel Alloy K-500 seriously lower tensile strength and ductility as a result of carbon diffusion. Experience has shown that heat treatments in some cases have improved surface integrity of damaged surfaces but not nearly as effectively as shot peening. Low temperature heat treatments are helpful in eliminating embrittlement in operations where hydrogen may be picked up during processing such as in plating. Elimination of hydrogen is time and temperature dependent and also depends upon the alloy being treated. Steels, for example, are often treated at about 375-400°F for periods of 8 hours or more.

33. Abrasive Tumbling is an Effective Process for Improving Surface Properties Including Fatigue

This process is less applicable than shot peening for many of the very large parts required for aerospace. Both abrasive tumbling and shot peening usually require an added polishing operation when very high finish requirements must be met. Care must be taken not to remove the favorable surface layer established by peening or tumbling. Abrasive tumbling can be used to reverse unfavorable tensile stresses by inducing a compression stressed surface layer.

34. Washing Procedures Should Be Employed for Critical Parts and Assemblies in Order to Remove All Traces of Cutting Fluids Which May Cause Stress Corrosion

Typical compounds which are suspect are sulfur compounds on aluminum and nickel base alloys and chlorine compounds on titanium alloys. Currently, some companies do not allow any chlorine-containing cutting fluids to be used in processing titanium parts which are to be used at room or elevated temperatures. Other companies use this precaution only for parts which are subjected to temperatures over 500°F. For applications at less than 500°F, carefully controlled washing procedures are often used to remove the chlorinated and sulfurized cutting oils. These fluids are particularly effective in chip removal operations such as drilling, tapping, and broaching. Since no complete agreement exists among manufacturers regarding cutting fluid practices, subcontractors are obliged to follow the policies and procedures established by the prime contractor.

35. Protection of Parts

Parts should not be stored for extended periods without being carefully washed and then covered with a coating or oil for corrosion prevention.

INSPECTION

36. Inspection Practices Should be Reviewed and Amplified to Meet Surface Integrity Requirements

There are some nondestructive as well as destructive testing practices which are being employed to test for surface condition.

a. Microscopic examination including microhardness testing is used on a sampling basis in order to determine the kind of surface layer being produced plus the layer depth. This method may be used to check for microcracks, pits, folds, tears, laps, built-up edge, intergranular attack, shorting, etc. Since many surface alterations are shallow, it is essential to use good edge retention techniques for microscopic examination. See Guideline 39 for details.

b. White layer or overtempered martensite produced during grinding of steels can be detected by immersion etching using 3-5 percent aqueous nitric acid solution. The procedures used vary among producers and are quite detailed and very exacting, consisting

essentially of appropriate and specific precleaning, etching, and post-etching procedures, including cleaning, drying, and application of rust inhibitors.

c. Magnetic particle, penetrant inspection, ultrasonic testing, and eddy current techniques are recommended for detecting macro-cracks. Most of the inspection techniques currently being used should be further refined by using more care in their application. Direct visual examination should be supplemented by macroscopic examination at low and medium magnification (5-20X).

d. X-ray diffraction methods are available to detect residual surface stresses. This method may be helpful in process development as well as for spot checking of finished parts. However, X-ray diffraction can only detect stresses within a few tenths of the surface and has the disadvantage of being expensive. The entire residual stress profile in the surface layer can be destructively determined by using X-ray diffraction plus etch techniques or by a deflection-etch technique.

37. Accidents Which Occur During Processing Should be Reported to Quality Control

Operators should be instructed to notify supervision of all accidents or damage including all visual evidence of damage. Grinding burn, breaking of drills, reamers or taps in holes, and shorting of electrodes in both EDM and ECM are examples of the type of mishaps which should be reported. Cleanup of surface discoloration is not necessarily sufficient to remove all of the damage which may extend several thousandths below the surface. In case of damage, parts should be subject to systematic review action.

SURFACE FINISH

38. From Surface Integrity Data Developed to Date, It Appears That for Structural Components Having a Surface Finish in a Range of 10-125 Microinches AA, Surface Finish Cannot Itself Be Used as a Measure of or For Control of Surface Integrity as Evaluated by Fatigue Testing

Until additional much needed data are made available, manufacturers of critical components are encouraged to develop experimental programs

for the purpose of opening up surface finish requirements, thereby reducing costs. Data upon which the above comments were based are:

Test No.	Material and Test Conditions[1]	Surface Finish (AA)	ENDURANCE LIMIT (KSI) HIGH CYCLE FATIGUE (10^7 cycles fully reversed bending)
	4340 (Q&T, 50 R_c)		
1	Longitudinal surface grind using gentle or low stress conditions and tested with fatigue stress parallel to lay	8 65 127	117 110 100
2	Transverse surface grind using gentle or low stress conditions and tested with fatigue stress perpendicular to lay	11 58 128	120 100 85
3	Longitudinal surface grind using an abusive condition (surface has untempered and overtempered martensite) and tested with fatigue stress parallel to lay	29 64 97	65 65 65
	Ti-6Al-6V-2Sn (ST&A, 42 R_c)		
4	End milling - end cutting using sharp cutter and tested with fatigue stress perpendicular to lay	13 55 125	82 82 82
	Inconel Alloy 718 (ST&A, 44 R_c)		
5	Turning - facing using sharp cutter and tested with fatigue stress perpendicular to lay	25 58 118	60 60 60

(1) Note: For a given test number the same basic test conditions were used to generate each of the three surface finishes. The different finishes within a given test were generated by varying feeds, cutting angles, wheel dressing, etc., as appropriate

39. Systematic Metallurgical and Mechanical Testing Programs for Establishing and Controlling Surface Integrity are Essential for Highly Critical Parts

As noted previously, these Guidelines are simply general recommendations which should be supplemented by very specific data in order to accommodate individual critical design requirements. Three types of evaluation programs are suggested. These programs differ in the extent of data which they provide and must be tailored to meet a plant's specific needs. These are arbitrarily designated as:

a. Minimum Data Set
b. Standard Data Set
c. Extended Data Set

a. The Minimum Data Set is essentially metallographic information supplemented with microhardness measurements and conventional surface finish measurements as follows:

Surface Finish

Macrostructure (10X or less)
  Macrocracks
  Macroetch Indications

Microstructure
  Microcracks
  Plastic Deformation
  Phase Transformations
  Intergranular Attack
  Pits, Tears, Laps, Protrusions
  Built-up Edge
  Melted and Redeposited Layers
  Depletion by Vaporization
  Selective Etching

Microhardness

Metallography affords a very simple approach for determining visual changes in the surface layer at higher magnification. Careful mounting and polishing techniques must be employed to achieve good edge preparation. In this way, heat affected layers can be identified, including melting or changes in the grain structure resulting from phase transformations or plastic deformation. Cracks are also detected readily and surface

roughness, pits, tears, laps and built-up edge can be identified microscopically. The following procedure has been used effectively:

1) Section samples carefully and cast in a mold with a mixture of an epoxy resin and suitable hardener plus fine grit pellitized aluminum oxide filler.

2) Place the mounts in a vacuum chamber during the setting period. (This step facilitates air removal and improves adherence of the mounting compound to the surface of the specimen.)

3) Cure the mounts at a temperature not exceeding 70°F for approximately 12 hours.

4) Grind and polish specimens metallographically by using a positive positioning polishing unit. Successively finer silicon carbide papers followed by diamond paste on suitable cloths are used to achieve the metallographic polish.

b. The Standard Data Set is designed to provide more in-depth data for the more critical applications which are influenced by surface integrity. It consists of:

Minimum Data Set
+
Fatigue Tests (Screening)
Stress Corrosion Tests
Residual Stress and Distortion

The Standard Data Set includes surface metallography studies. In addition, three mechanical properties are suggested for evaluation because they are generally significant in surface integrity situations. These are residual stress, fatigue, and stress corrosion. Distortion as related to residual stress becomes an important consideration because the emphasis on high-strength-to-weight ratios leads to fragile parts requiring high dimensional accuracy. Stress corrosion tests are very important because many highly stressed components are subjected to environments which can cause cracking in parts carrying residual surface tensile stresses. Screening type fatigue tests isolate the most important variables which should be considered, thereby providing a strong base for making manufacturing decisions. A suggested format for summarizing important data from a Standard Data Set is shown on page 44.

c. The Extended Data Set provides data gathered from statistically designed fatigue programs and yields data suitable for detailed designing. The Extended Data Set consists of:

Standard Data Set (Includes Minimum Data Set)

+

Fatigue Tests (Extended to obtain design data)

Additional Mechanical Tests
- Tensile
- Stress Rupture
- Creep

Screening tests (from the Standard Data Set) as well as extended fatigue studies take various forms, but always the extended programs can be expected to require many more tests in order to develop the necessary confidence limits. For highly critical parts, it is usually customary to run full-scale component tests.

To round out a surface integrity package, extended testing may logically require evaluation of surface integrity effects on tensile, stress rupture, creep, and other material properties under unusual environmental conditions.

SUGGESTIONS FOR IMPLEMENTING SURFACE INTEGRITY

40. Positive Steps Should be Taken to Increase Awareness of Surface Integrity

Education and Training

Manufacturing and product engineering personnel on the average are not sufficiently acquainted with the many types of surface alterations which can be produced during material removal operations. Product or design engineers generally do not realize that high temperatures prevail at workpiece and tool interfaces, while manufacturing people often do not realize the extent to which metallurgical changes occur and how seriously they lower mechanical properties. This situation points out the advisability of having short educational efforts to help increase general cognizance of the importance of surface integrity control.

In addition to the general educational programs, specific training is required for machine operators and quality control personnel. Some companies require qualification of personnel in order to perform drilling and reaming of holes. Other plants give short courses on how to inspect for rehardened and overtempered martensite in the manufacture of high strength steel components.

Particular attention should be given to the necessity for maintaining specified operating parameters. Machine operators should be thoroughly trained to follow the proper procedures outlined by manufacturing engineering. All parameters for material removal should be specified by manufacturing engineering. These include tool material, tool geometry, cutting speed, feed, cutting fluid, and tool life (maximum number of parts per tool grind) for chip removal operations. Similarly, appropriate parameters must be set up for operations such as grinding, EDM, and ECM. Machinists should be informed as to the reason and necessity for maintaining good surface integrity and surface quality and should be made aware that currently it is not possible to guarantee maintenance of surface integrity by final part inspection. Management needs to be ever alert to the desire on the part of operators to try "just one more notch" on the control. Without requalification, this relaxation of standards may result in loss of surface integrity.

Publication of In-House Guidelines

The Guideline concept has been used by some organizations to assist in the implementation of surface integrity processing. Booklets can be designed to fit the specific needs of a company, division, or department. Guidelines are particularly useful prior to the development of practical and meaningful specifications.

Specifications

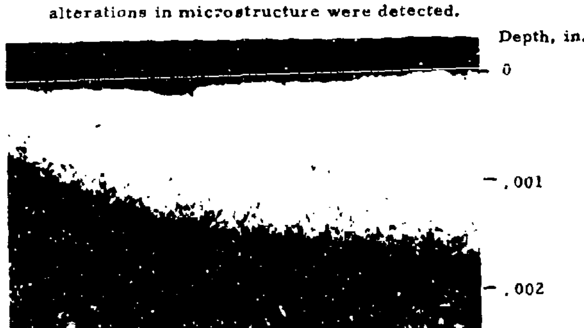
Preparation of processing specifications is most highly recommended for critical parts. Some of the aerospace producers have in fact already written detailed manufacturing specifications incorporating machining parameters and procedures in an effort to maintain surface integrity. These specifications, even though widely used in subcontract work, are generally considered proprietary and under the control of the prime contractor. It is suggested that manufacturing engineering departments of the large prime aerospace producers be contacted directly concerning the availability of their specifications.

References - Sources of Surface Integrity Data

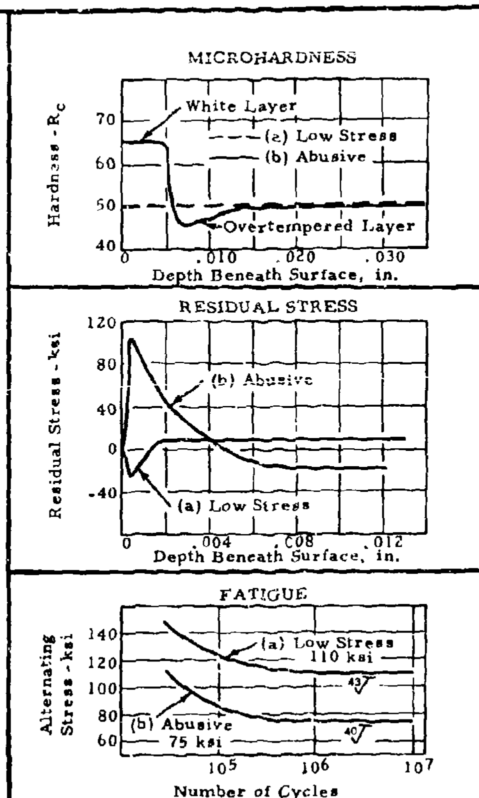
In addition to References 1-9 (page 427) cited in these guidelines, the Bibliography on pages 428 to 430 provides both general and specific surface integrity information. An additional Surface Integrity Bibliography, containing 665 references, is included in "Surface Integrity of Machined Structural Components," Interim Report IR-721-8(I), 1968, Contract F33615-68-C-1003.

On a continuing basis data are available from the Machinability Data Center (MDC). MDC is collecting information and data on surface integrity as they become available and is evaluating the data for application in the material removal industry. Specific inquiry services are available to U.S. Government agencies and private industry. Inquiries should be directed to Supervisor, Technical Inquiries, Machinability Data Center, 3980 Rosslyn Drive, Cincinnati, Ohio 45209, Telephone: 513-271-9510, TWX: 810-461-2840.

(a) Low Stress Conditions - No visible surface alterations in microstructure were detected.



(b) Abusive Conditions - A total heat affected zone of .013 in. was produced. The white layer shown above is 65 R_c and approximately .001-.002 in. deep but in some sections was up to .005 in. deep.



SURFACE CHARACTERISTICS PRODUCED BY GRINDING
AISI 4340 STEEL, QUENCHED AND TEMPERED, 50 R_c

5. PROCEDURES

5.1 Procurement and Certification of Test Materials

All materials used in the fulfillment of this contract were ordered either as 1/4" rolled plate or 1/4" thick castings. This thickness of raw material was chosen to allow for removal of sufficient stock from the surface of the material so as to avoid the influence of various surface conditions which might be present. A summary of the identification and certification of each of the materials included in this report is as follows:

5.1.1 AISI 4340 Steel

Applicable Specification: AMS-6359

Source: Republic Steel Corporation, Heat No. 3820773

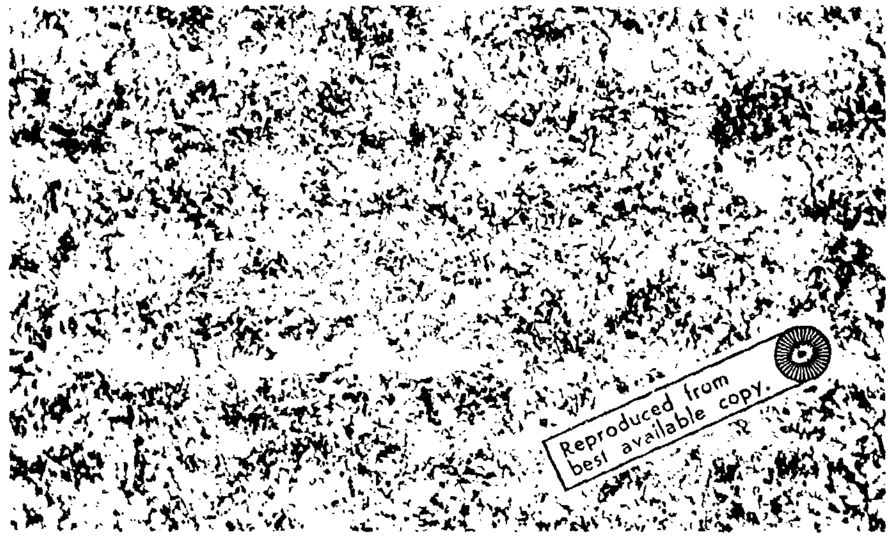
The specified melt chemistry of this material, in comparison with the check analysis determined by F. C. Broeman & Company, Cincinnati, Ohio, is indicated as follows:

	Specification	Check Analysis
Carbon	0.38 - 0.43	0.42
Manganese	0.60 - 0.80	0.70
Silicon	0.20 - 0.35	0.25
Phosphorus	0.025 max.	0.015
Sulfur	0.025 max.	0.012
Chromium	0.70 - 0.90	0.78
Nickel	1.65 - 2.00	1.79
Molybdenum	0.20 - 0.30	0.27
Copper	0.35 max.	0.20
Iron	Remainder	--

The grain size as called out by the above specification was for predominantly ASTM 5 or finer with occasional grains as large as 3. The subject heat of material indicated an average grain size of 10 which was quite uniform.

The subject heat of material, upon sampling the entire cross section of the 1/4 in. plate, indicated a maximum visible decarburization as judged by microstructure of less than 0.002 in. A photomicrograph of this microstructure at a magnification of 1000X is shown below.

5.1.1 AISI 4340 Steel (continued)



No mechanical properties requirements were covered in the applicable specification for this alloy; no specific determinations were made on the as-received material.

Mechanical properties determinations for this alloy is covered in Section 5.2.1.

5.1.2 4340 Modified

Applicable Specification: The Boeing Company, BMS 7-26G

Source: Republic Steel Corporation, Heat No. 3923243.

The specified melt chemistry of this material, in comparison with the check analysis determined by F. C. Broeman & Company, Cincinnati, Ohio, was as follows:

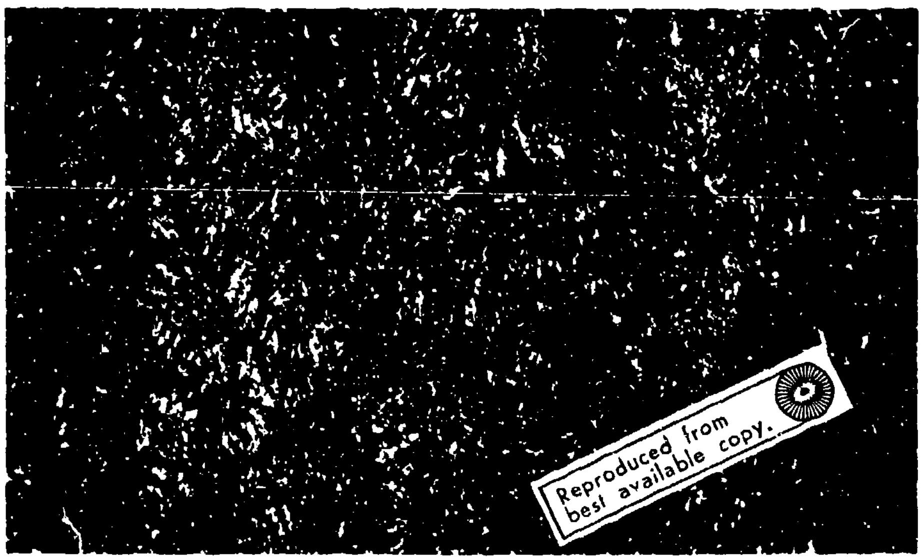
5.1.2 4340 Modified (continued)

	Specification	Check Analysis
Carbon	0.38 - 0.43	0.40
Manganese	0.60 - 0.90	0.85
Silicon	1.50 - 1.80	1.72
Phosphorus	0.010 max.	0.01
Sulfur	0.010 max.	0.008
Chromium	0.70 - 0.95	0.90
Nickel	1.65 - 2.00	1.76
Molybdenum	0.30 - 0.50	0.40
Vanadium	0.05 - 0.01	0.07
Iron	Remainder	--

The specified grain size for this alloy is an average of ASTM 5 or finer with the maximum permissible size ASTM 3. This heat of 4340 modified exhibited a grain size of 10 as measured metallographically.

A maximum depth of decarburization of 0.015 in. is allowable under BMS 7-26G. The plate used for this program exhibited an average partial decarburization to 0.007 in.

A photomicrograph of this steel in the as-received condition is shown below at 1000X.



5.1.3 18% Nickel Grade 300 Maraging Steel

Applicable Specification: The Boeing Company, BMS 7-200

Source: Republic Steel Corporation, Heat No. 3911137

The specified melt chemistry of this material, in comparison with the check analysis supplied by the vendor, is as follows:

	Specification	Check Analysis
Carbon	0.015 max.	0.006
Manganese	0.05 max.	0.05
Silicon	0.05 max.	0.05
Phosphorus	0.010 max.	0.007
Sulfur	0.010 max.	0.006
Nickel	18.00-19.00	19.00
Cobalt	8.50- 9.50	8.93
Molybdenum	4.60- 5.20	4.97
Titanium	0.60- 0.80	0.65
Aluminum	0.05- 0.15	0.08
Boron	0.003 max.	0.003
Calcium	0.05 max.	0.06
Zirconium	0.02 max.	0.007
Iron	Balance	--

A photomicrograph of this maraging steel in the as-received condition is shown below at 1000X.

5.1.4 Titanium 6Al-4V, Beta Rolled

Applicable Specification: The Boeing Company, XBMS 7-174, Condition 1, mill annealed.

Source: Reactive Metals, Inc., Heat No. 302493.

The specified melt chemistry of this material, in comparison with the check analysis determined by F.C. Broeman & Company, Cincinnati, Ohio, and Ledoux and Company, Teaneck, New Jersey, was as follows:

	Specification	Check Analysis
Titanium	Remainder	--
Aluminum	5.5 - 6.75	6.20
Vanadium	3.5 - 4.5	3.82
Iron	0.25 max.	0.12
Carbon	0.08 max.	0.07
Hydrogen	0.0125 max.	0.0135
Oxygen	0.175 max.	0.119
Nitrogen	0.03 max.	0.015
Other Impurities	0.40 max.	--

The heat treatment specified for Condition 1 of this alloy in comparison to that used at the mill source for processing this material was as follows:

Specification	Heat No. 302493
1350 ± 25°F to 1450 ± 25°F/ 15 minutes to 8 hours/air or furnace cool	1450°F/15 minutes/air cooled (production annealed)

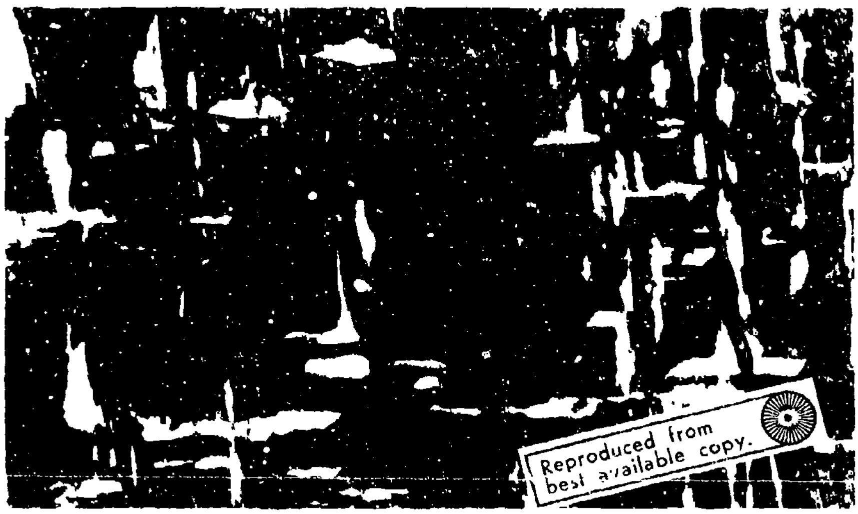
The tensile properties per the applicable specification in comparison with those actually measured by Metcut are summarized below.

	Specification	Measured Properties
Thickness	0.188 - 2.000 in.	0.25
UTS, psi	130,000 minimum	144,000*
0.2% Y.S., psi	120,000 minimum	131,000*
Elongation, % in 4D	10.0 minimum	12.5

* Values reported are averages of three tests

5.1.4 Titanium 6Al-4V, Beta Rolled (continued)

The applicable specification indicates that the microstructure shall consist of 100% acicular alpha phase when examined under conditions detailed in the specification. The microstructure shown below at 500X magnification, typical of the test material, conforms to this requirement.



The hardness range of Titanium 6Al-4V is not a stated requirement of this Boeing specification. For purposes of record, however, it was determined to be in the range of 31-33 R_c.

5.1.5 Titanium 6Al-6V-2Sn

Applicable Specification: MIL-T-9046F (Type III-E)

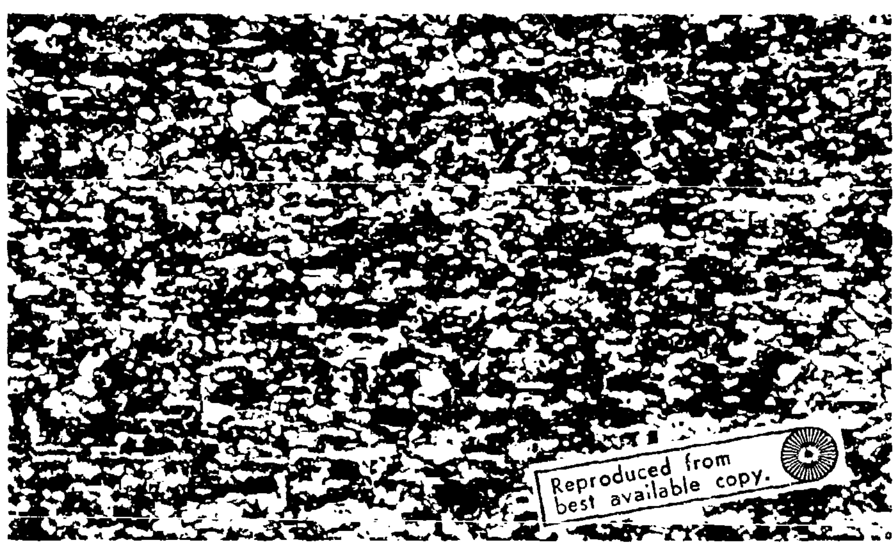
Source. Titanium Metals Corporation of America (Heat K-5228)

The specified melt chemistry of this material, in comparison with the check analysis determined by F. C. Broeman & Company, Cincinnati, Ohio, and Ledoux and Company, Teaneck, New Jersey, was as follows:

5.1.5 Titanium 6Al-6V-2Sn (continued)

	Specification	Check Analysis
Aluminum	5.0 - 6.0	5.46
Tin	1.5 - 2.5	2.46
Vanadium	5.0 - 6.0	5.20
Iron	0.35 - 1.00	0.36
Carbon	0.05 max.	0.045
Nitrogen	0.05 max.	0.021
Hydrogen	0.015 max.	0.014
Oxygen	0.20 max.	0.175
Copper	0.35 - 1.00	0.62
Titanium	Balance	--

A photomicrograph of this titanium alloy in the as-received condition is shown below at 1000X.



Mechanical properties determinations, made after the desired heat treatment was accomplished, are contained in Section 5.2.5.

5.1.6 Titanium 6Al-2Sn-4Zr-2Mo

Applicable Specification: The General Electric Company, B50TF21-S2, Class A, Duplex Annealed

Source: Titanium Metals Corporation of America, Heat No. K-5441

The melt chemistry of this material as specified, in comparison with the check analysis supplied by the vendor, was as follows:

	Specification	Check Analysis
Aluminum	5.50 - 6.50	6.1
Tin	1.80 - 2.20	2.2
Zirconium	3.60 - 4.40	4.2
Molybdenum	1.80 - 2.20	2.0
Iron	0.25 max.	0.07
Carbon	0.05 max.	0.022
Oxgyen	0.15 max.	0.11
Nitrogen	0.05 max.	0.008
Hydrogen	0.015 max.	0.007

A photomicrograph of this titanium in the as-received condition is shown below at 1000X.

5.1.7 Inconel 718

Applicable Specification: The General Electric Company, B50TF14-S4, Class A, mill annealed.

Source: Allvac Metals Company, Heat No. 6604.

The melt chemistry of this material as specified, in comparison with the check analysis determined by F. C. Broeman & Company, Cincinnati, Ohio, was as follows:

	Specification	Check Analysis
Carbon	0.02 - 0.08 max.	0.03
Manganese	0.35 max.	0
Silicon	0.35 max.	0.15
Sulfur	0.015 max.	0.007
Phosphorus	0.015 max.	0.01
Chromium	17.00 - 21.00	19.52
Iron	16.50 - 20.50	16.65
Cobalt	1.00 max.	0.35
Molybdenum	2.80 - 3.30	3.03
Columbium + Tantalum	4.75 - 5.50	5.11
Titanium	0.75 - 1.15	1.01
Aluminum	0.30 - 0.70	0.37
Boron	0.006 max.	0.005
Copper	0.30 max.	less than 0.05
Nickel	Remainder	--

The hardness of this material following a 1700-1800°F mill anneal is specified as 100 R_B maximum. The hardness of the subject heat of material was determined to be 93-94 R_B. A part of this G. E. specification involves converting the material from the mill annealed condition (Class A) to the solution treated and aged condition (Class B), and checking certain mechanical properties in the Class B condition. After conversion to the Class B condition, the hardness is specified to fall in the range of 38-48 R_C. Following this procedure, the subject heat of material indicated a hardness of 43-44 R_C. The tensile properties, after heat treatment of samples converting them to B50TF14, Class B, are summarized as follows in comparison to the applicable specification:

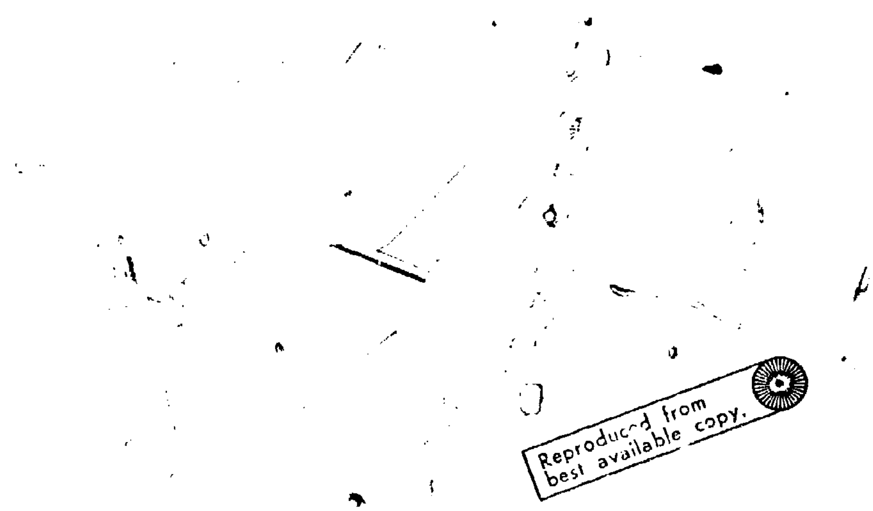
5.1.7 Inconel 718 (continued)

	Specification Minimums		Measured Properties	
	Room Temp.	1200° F	Room Temp.	1200° F
UTS, psi	180,000	140,000	208,000*	166,000*
0.2% Y.S., psi	150,000	120,000	160,000*	131,000*
Elongation, % in 4D	12.0	5	22*	25*

Stress rupture properties after conversion by heat treatment to Class B, and in comparison to the applicable specification, are as summarized below.

	Specification	Measured Properties
Temperature	1200° F	1200° F
Stress, psi	100,000	100,000
Life, hours	20 min.	70 hours, removed without failure*

The grain size of the Inconel 718 in the Class A condition is specified as an average of ASTM 5 or finer, with a maximum permissible grain size of ASTM 3. This heat of material was judged as having an average uniform grain size of ASTM 5-6 in the as-received condition (Class A), and ASTM 6-10 after conversion by heat treatment to Class B. A photomicrograph of the subject heat of material at 500X in the Class A as-received condition is as follows:



* Values reported are averages of three tests

5.1.8 AF 95

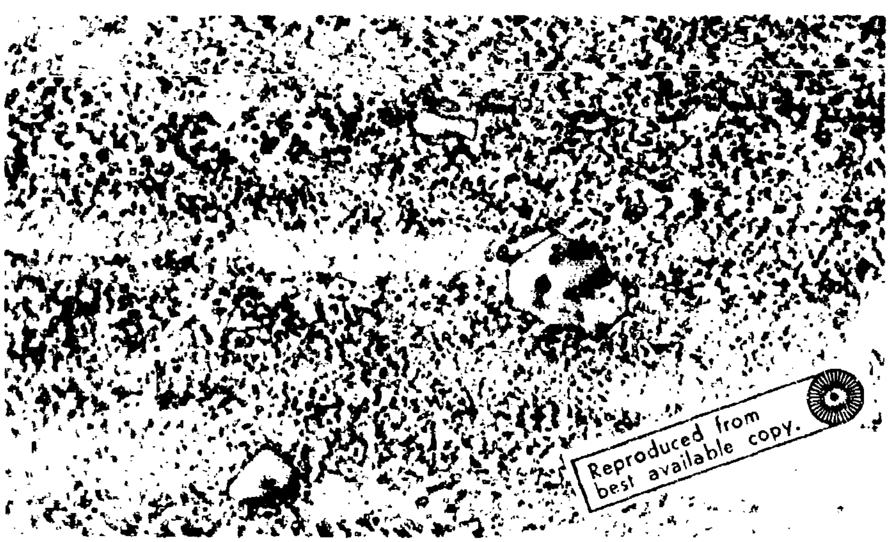
Applicable Specification: General Electric Company, C50TF31-3(T)

Source: Universal Cyclops Specialty Steel Division, Heat No. KH 70160K11

The specified melt chemistry of this material, in comparison with the check analysis supplied by the vendor, is as follows:

	Specification	Check Analysis
Carbon	0.13 - 0.17	0.14
Manganese	0.15 max.	0.02
Silicon	0.20 max.	0.06
Phosphorus	0.015 max.	0.006
Chromium	0.015 max.	0.001
Cobalt	13.00 - 15.00	14.74
Molybdenum	7.00 - 9.00	8.18
Columbium	3.30 - 3.70	3.54
Zirconium	3.30 - 3.70	3.40
Titanium	0.03 - 0.07	0.034
Aluminum	2.30 - 2.70	2.35
Boron	3.30 - 3.70	3.53
Tungsten	0.006 - 0.015	0.010
Nickel	3.30 - 3.70	3.50
	Remainder	--

A photomicrograph of this nickel base alloy in the as-received condition is shown at 1000X below.



5.1.9 AF2-1DA

Applicable Specification: Cyclops Corporation (Internal)

Source: Universal-Cyclops Specialty Steel Division,
Heat No. K 70162K11

The melt chemistry of this material as specified by Universal-Cyclops' internal specification, in comparison with the check analysis supplied by the vendor, is as follows:

	Specification	Check Analysis
Carbon	0.32 - 0.38	0.34
Chromium	11.50 - 12.50	12.16
Cobalt	9.50 - 10.50	9.96
Molybdenum	2.80 - 3.20	3.02
Tungsten	5.80 - 6.20	6.15
Tantalum	1.30 - 1.70	1.65
Aluminum	4.50 - 4.70	4.57
Titanium	2.80 - 3.20	3.02
Boron	0.010 - 0.018	0.014
Zirconium	0.05 - 0.15	0.12
Iron	1.00 max.	--
Nickel	Balance	--
Sulfur	--	0.003
Phosphorus	--	0.001

A photomicrograph of this nickel base alloy in the as-received condition is shown below at 1000X.

5.1.10 Rene' 80

Applicable Specification: General Electric Company, C50TF28-S3, Class C, As Cast

Source: Howmet Corporation, Austenal Microcast Division, Heat No. 101V9419

The melt chemistry of this material, per the above specification and as obtained by the vendor in his check analysis, is given below.

	Specification	Check Analysis
Carbon	0.15 - 0.19	0.16
Manganese	0.20 max.	0.01
Silicon	0.20 max.	0.10
Sulfur	0.015 max.	0.002
Chromium	13.70 - 14.30	14.00
Titanium	4.80 - 5.20	4.88
Boron	0.010 - 0.020	0.015
Aluminum	2.80 - 3.20	3.07
Tungsten	3.70 - 4.30	3.83
Molybdenum	3.70 - 4.30	4.00
Molybdenum + Tungsten	7.70 min.	7.83
Cobalt	9.00 - 10.00	9.48
Iron	0.20 max.	0.18
Zirconium	0.02 - 0.04	0.04
Nickel	Balance	--
$\overline{N}_V 3$	2.32 max.	2.28

A photomicrograph of this nickel base alloy in the as-received condition is shown below at 1000X.

5.2 Preparation and Heat Treatment of Specimen Blanks

Coupons for all test specimens other than the castings were cut from the longitudinal direction of the 1/4" plate obtained using a heavy duty band saw. An exception to this was in the case of AF 95 where coupons were cut from the shorter dimension of the cross rolled plate. Since the plate was cross rolled, the orientation of the coupons was not considered to be of prime importance. The change in orientation was made in the case of AF 95 due to warpage in the material as supplied by the mill source.

After sectioning, coupons were heat treated to the required conditions as outlined in this section. Heat treated coupons were then rough machined, subjected to the test cutting operation, and subsequently finished for testing as described in Section 5.3.

A summary of the various heat treatments used on the alloys covered by this report and the mechanical properties resulting from these treatments is summarized in the following sections.

5.2.1 AISI 4340, 50 R_c

It was desired to work this alloy in the quenched and tempered condition at a strength level in the 250-270 ksi range. The following heat treatment was used:

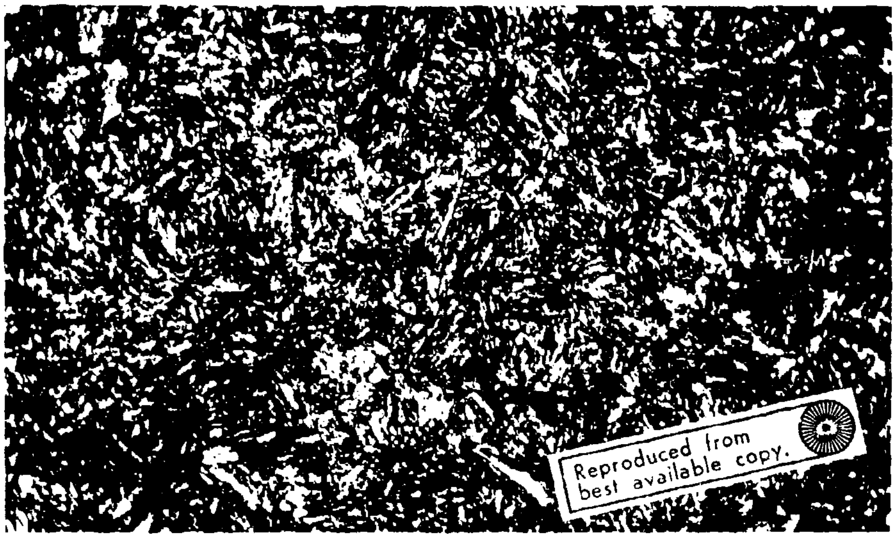
Normalize:	1600°F/1 hour/air cool
Quench:	1550°F/1 hour/oil quench
Temper:	550°F/2 hours/air cool

Properties of samples of the AISI 4340 subjected to this heat treatment were measured to be as follows:

UTS:	259,000 psi	0.2% Y.S.:	221,000 psi
R.A.:	50.5%	Elongation:	11.5%
Hardness:	49-51 R_c		

A photomicrograph showing this heat treated condition is presented as follows at a magnification of 1000X:

5.2.1 AISI 4340, 50 R_C (continued)



5.2.2 4340 Modified, 53 R_C, 285 ksi

It was desired to work with this alloy in the 275+ ksi range. The following hardening treatment was used to achieve this condition:

Normalize:	1675°F/1 hour/air cool
Austenize:	1600°F/1 hour/oil quench
Double Temper:	575°F/ 3 hours/air cool

The microstructure of 4340 modified following this heat treatment is shown as follows at 1000X.

5.2.2 4340 Modified, 53 R_C, 285 ksi (continued)

The resulting transverse mechanical properties which also confirm acceptability of this heat of material to BMS 7-26G, Class I, are as follows:

	Specification	Measured Properties
UTS, psi	275,000 minimum	287,000*
0.2% Y.S., psi	227,000 minimum	247,000*
R.A., % in 4D	25 minimum	37*

The hardness range of this material is not a stated requirement of this Boeing specification. The values obtained, however, were in the range of 52.5 - 53.5 R_C.

5.2.3 18% Nickel Grade 300 Maraging Steel, 54 R_C

This alloy was evaluated in the "double solution" and precipitation aged condition at an ultimate strength level of 285 ksi (minimum). The following heat treatment was used:

Solution: 1700°F/1 hour/forced air cool
1475°F/1 hour/forced air cool

Age: 900°F/6 hours/air cool

Properties of transverse samples of the 18% nickel maraging steel subjected to this heat treatment, which conforms to BMS 7-200, are as follows:

	Specification BMS 7-200	Measured Values Heat 3911127
UTS, psi	285,000 (min.)	315,000
0.2% Y.S., psi	275,000 (min.)	309,000
R.A., %	25 (min.)	47
Elongation, %	6 (min.)	9

* Values reported are averages of three tests

5.2.3 18% Nickel Grade 300 Maraging Steel, 54 R_c (continued)

The heat treated structure of this material is shown at 1000X in the following photomicrograph.

5.2.4 Titanium 6Al-4V, Beta Rolled

This alloy was evaluated in the mill annealed condition in which it was received from the alloy producer. No further heat treatment was carried out at Metcut. (The heat treatment used by the mill source for processing this alloy is indicated in Section 5.1.4).

5.2.5 Titanium 6Al-6V-2Sn, 42 R_c

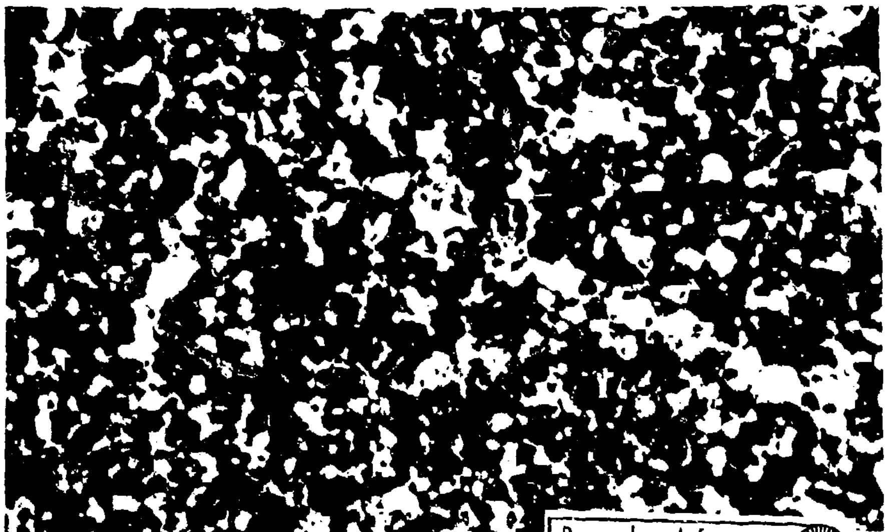
The solution and aging treatments selected for this alloy are as outlined in MIL-H-81200A. These conditions are as follows:

Solution Treatment: 1600° F/1 hour/water quench

Age: 1100° F/4 hours/air cool

A typical photomicrograph at 1000X of the resulting structure is shown below.

5.2.5 Titanium 6Al-6V-2Sn, 42 R_c (continued)



The tensile properties resulting from this heat treatment, which also show conformance to MIL-H-9046F are tabulated below.

	Specification	Measured Properties
UTS, psi	170,000 minimum	186,000*
0.2% Y.S., psi	160,000 minimum	174,000*
Elongation, % in 4D	8 minimum	12*

5.2.6 Titanium 6Al-2Sn-4Zr-2Mo, 36 R_c

It was desired to test this alloy in the solution treated and aged condition as detailed in General Electric Specification B50TF22-S2. These conditions are as follows:

Solution Treatment: 1750°F/1 hour/air cool

Age: 1100°F/8 hours/air cool

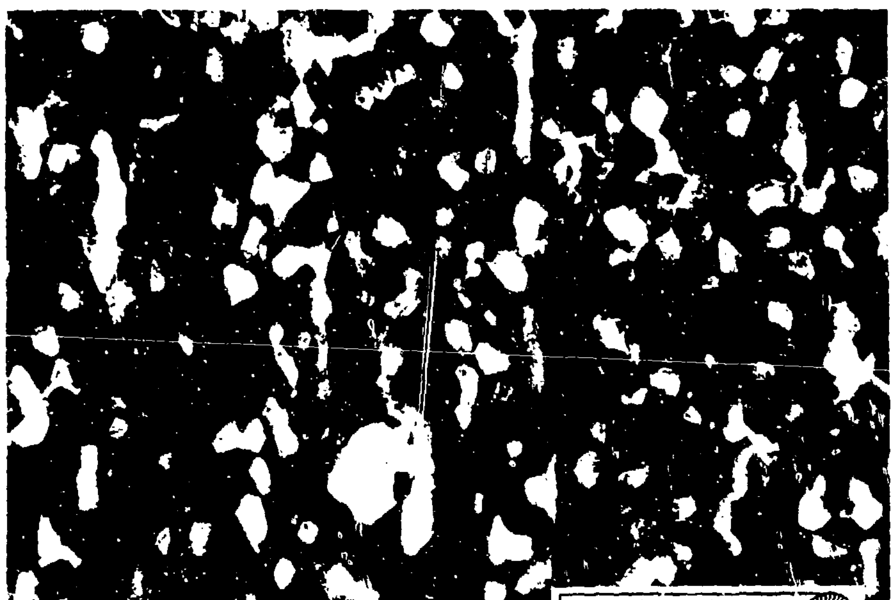
Average room temperature properties obtained on specimens heat treated per these conditions were as follows:

* Values reported are averages of three tests

5.2.6 Titanium 6Al-2Sn-4Zr-2Mo, 36 R_C (continued)

	Specification B50TF22	Measured Values Heat K-5441
UTS, psi	130,000 (min.)	160,000
0.2% Y.S., psi	120,000 (min.)	147,000
R.A., %	25 (min.)	39.5
Elongation, % in 4D	10 (min.)	16.5

The microstructure of the subject heat in the solution treated and aged condition is shown at 1000X in the following photomicrograph.



5.2.7 Inconel 718, 44 R_C

The solutioning and aging treatment selected for use with this alloy coincides with the Class B heat treatment per the applicable G. E. Specification, B50TF14-S4. This heat treatment is as follows:

Solution Treatment: 1700° F/1 hour/air cool

Age: 1325° F/8 hours/furnace cool at a rate of 100° F per hour to 1150° F. Hold 8 hours at 1150° F/ air cool

5.2.7 Inconel 718, 44 R_c (continued)

The microstructure of Inconel 718 following this heat treatment is shown below at 500X.

The resulting mechanical properties, previously obtained in order to verify conformance of this alloy to the applicable specification, are summarized in Section 5.1.7.

5.2.8 AF 95, 50 R_c

This alloy was evaluated in the solution treated and aged condition using the heat treatment specified in General Electric Specification C50TF31:

1650° F/24 hours/elevate to
2000° F/1 hour/oil quench
1400° F/16 hours/air cool

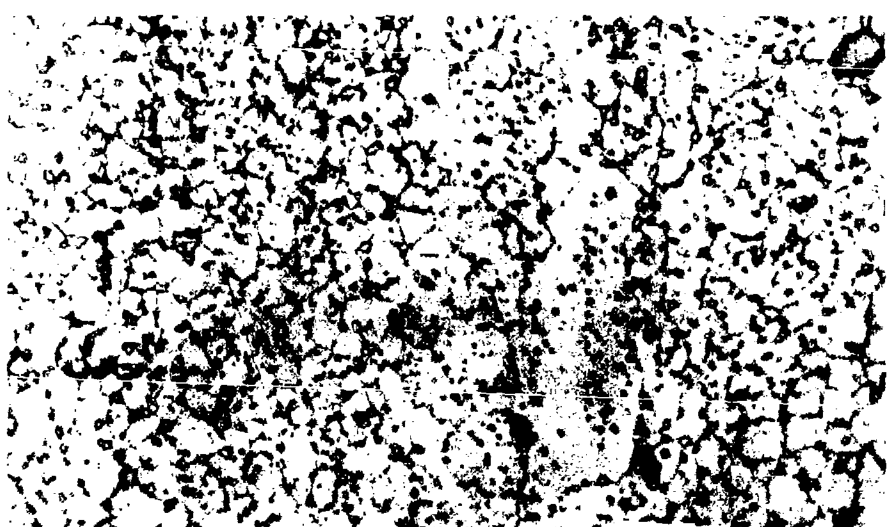
The average tensile properties, based on triplicate tests of the AF 95 material heat treated per the above conditions were determined to be as follows:

5.2.8 AF 95, 50 R_c (continued)

Measured Values, Heat No. KH 70160K11	Longitudinal Room Temp.	Longitudinal 1200°F	Transverse Room Temp.
UTS, psi	250,000	236,000	239,000
0.2% Y.S., psi	215,000	196,000	209,000
R.A., %	10.5	11.3	10.0
Elongation, % in 4D	11.0	11.5	9.5

The hardness of the AF 95 in this condition was measured as 49-50 R_c.

The heat treated structure of this material is shown at 1000X in the following photomicrograph.



5.2.9 AF2-1DA, 50 R_c

The heat treatment used for this alloy was the same solution and aging cycle used for AF 95, as follows:

5.2.9 AF2-1DA, 50 R_c (continued)

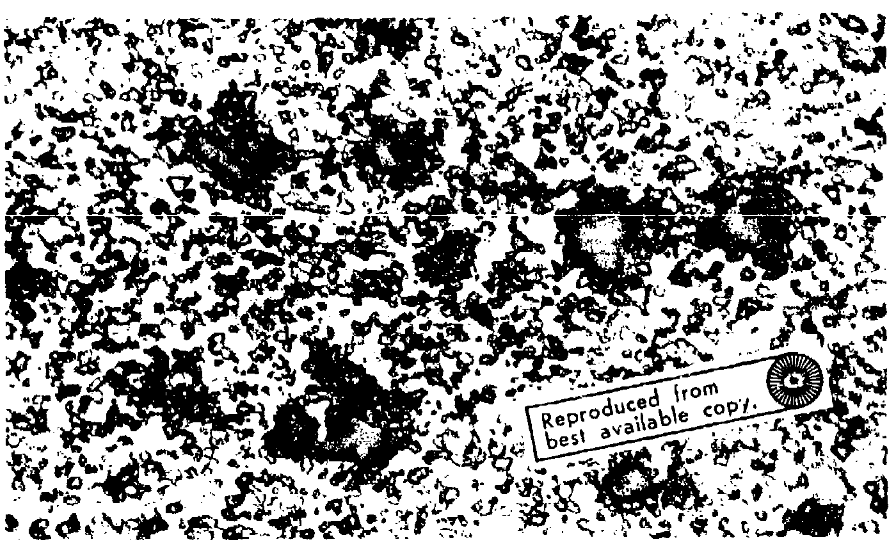
1650°F/24 hours/elevate to
2000°F/1 hour/oil quench
1400°F/16 hours/air cool

The tensile properties (average of three tests) for material heat treated per this condition are listed below:

	Measured Longitudinal Values Heat No. K 70162K11
UTS, psi	216,000
0.2% Y.S., psi	175,000
RA, %	11.5
Elongation, % in 4D	12.0

The hardness of the AF2-1DA following this heat treatment was 45-46 R_c.

Typical heat treated microstructure is shown at 1000X in the following photomicrograph.



5.2.10 Rene' 80, 40 R_c

It was desired to evaluate this nickel base alloy in the heat treated condition conforming to General Electric Specification C50TF28-S3, Class A. This heat treat cycle is as follows:

2225°F (vac.)/2 hours/argon quench
2000°F (vac.)/4 hours/argon quench
1925°F (vac.)/4 hours/furnace cool to
1200°F/1 hour/air cool
1550°F (vac.)/16 hours/fan air cool

Mechanical properties data supplied by the vendor as compared with the specification are given below:

Tensile Properties (1600°F):

	Measured Values Heat 101V9419	Specification C50TF28-S3
UTS, psi	101,000	90,000
0.2% Y.S., psi	90,000	70,000
RA, %	16 8	15

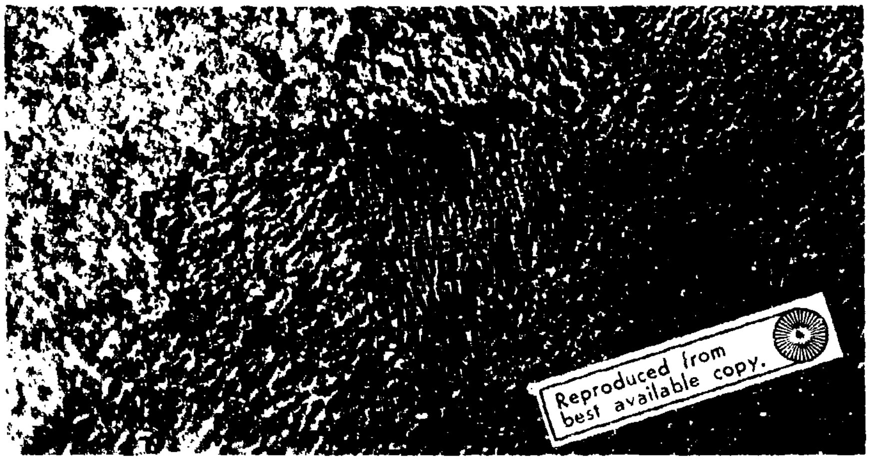
Stress Rupture (1800°F/27,500 psi)

Rupture Life (hours)	62.8	23
R.A., %	5.5	5

The hardness of the Rene' 80 following heat treatment was 38-40 R_c.

5.2.10 Rene' 80, 40 R_C (continued)

The microstructure of the heat treated condition for this alloy is shown at 1000X in the following photomicrograph.



5.3 Manufacture of Specimens

Following heat treatment, specimens were manufactured in accordance with the adjacent figures as follows:

Residual Stress Specimens, All Materials	Figure 6
High Cycle Fatigue Specimens, Grinding and Milling	Figure 7
High Cycle Fatigue Specimens, EDM, ECM, and Turning	Figure 8
Low Cycle Fatigue Specimens, Grinding and Milling	Figure 9 *
Low Cycle Fatigue Specimens, EDM, ECM, and Turning	Figure 10 *
Stress Corrosion Specimens	Figure 11

In evaluating several of the conditions covered in this program, surface characteristics were studied both perpendicular and parallel to the machining lay. Definitions covering the various machining orientations used relative to the specimen direction are summarized in Figure 12.

The layout and blanking of specimens as well as specific procedures used for the various test cut operations are summarized in the various sections of Appendix I. This appendix covers the general preparation of specimens (I-1) as well as the various cutting and post-processing procedures used (I-2 through I-10). Summaries of the specific cutting parameters are contained in Tables I through XI.

* There were some slight modifications in length and width to suit certain materials/test equipment requirements.

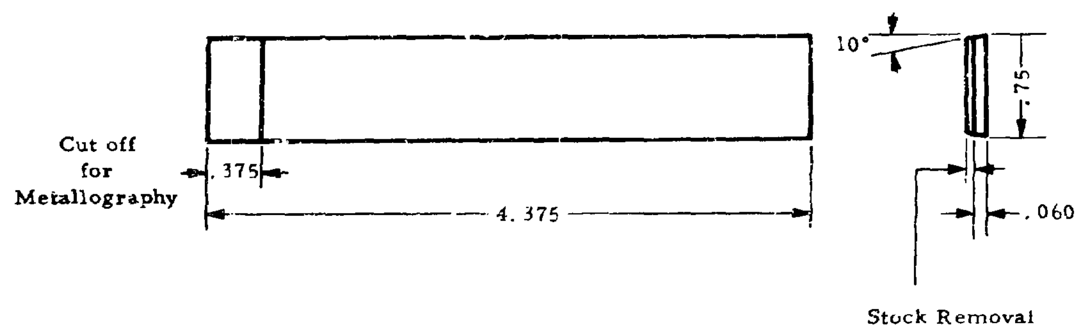


Figure 6
RESIDUAL STRESS SPECIMEN

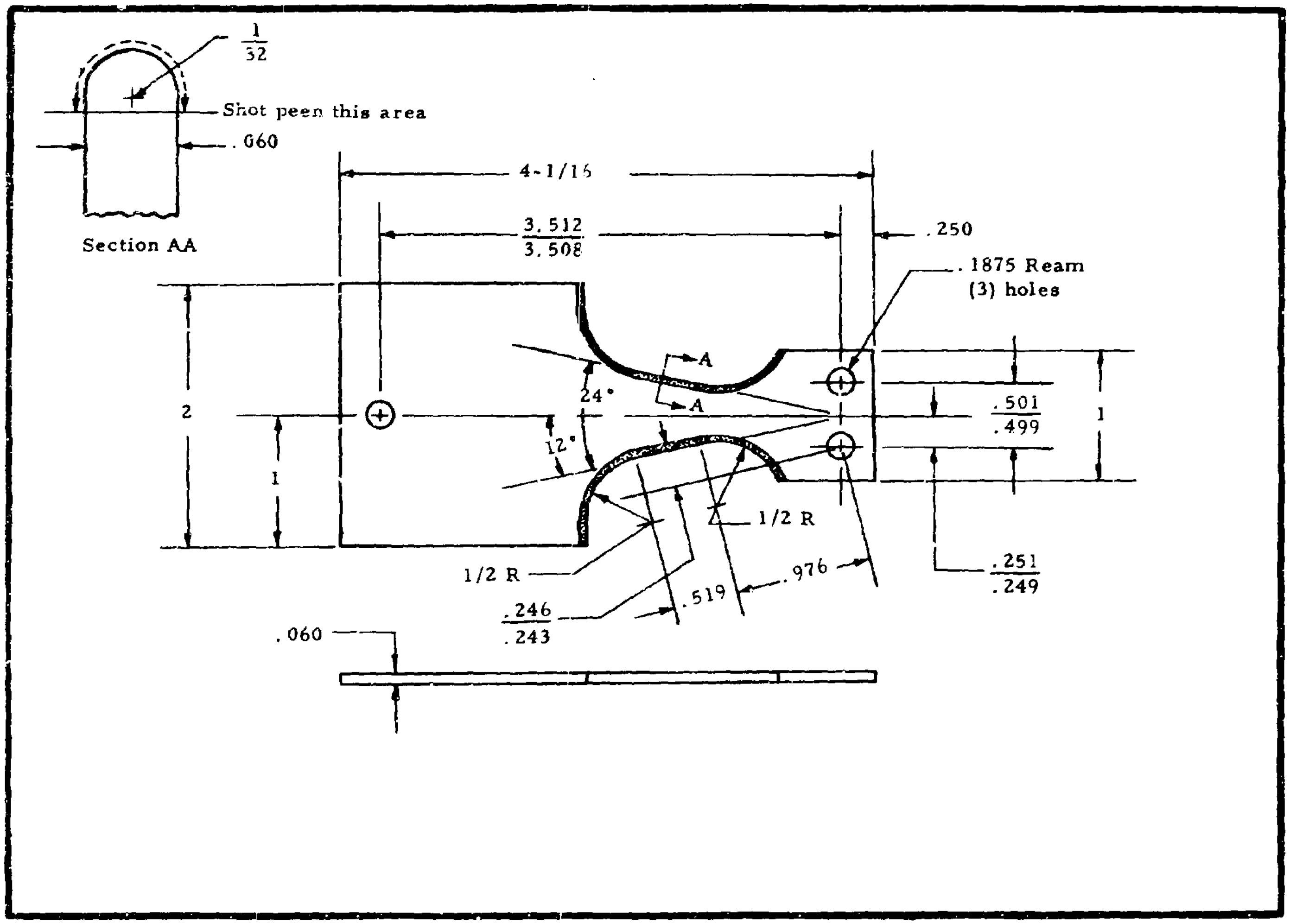


Figure 7
HIGH CYCLE FATIGUE SPECIMEN - GRINDING AND MILLING

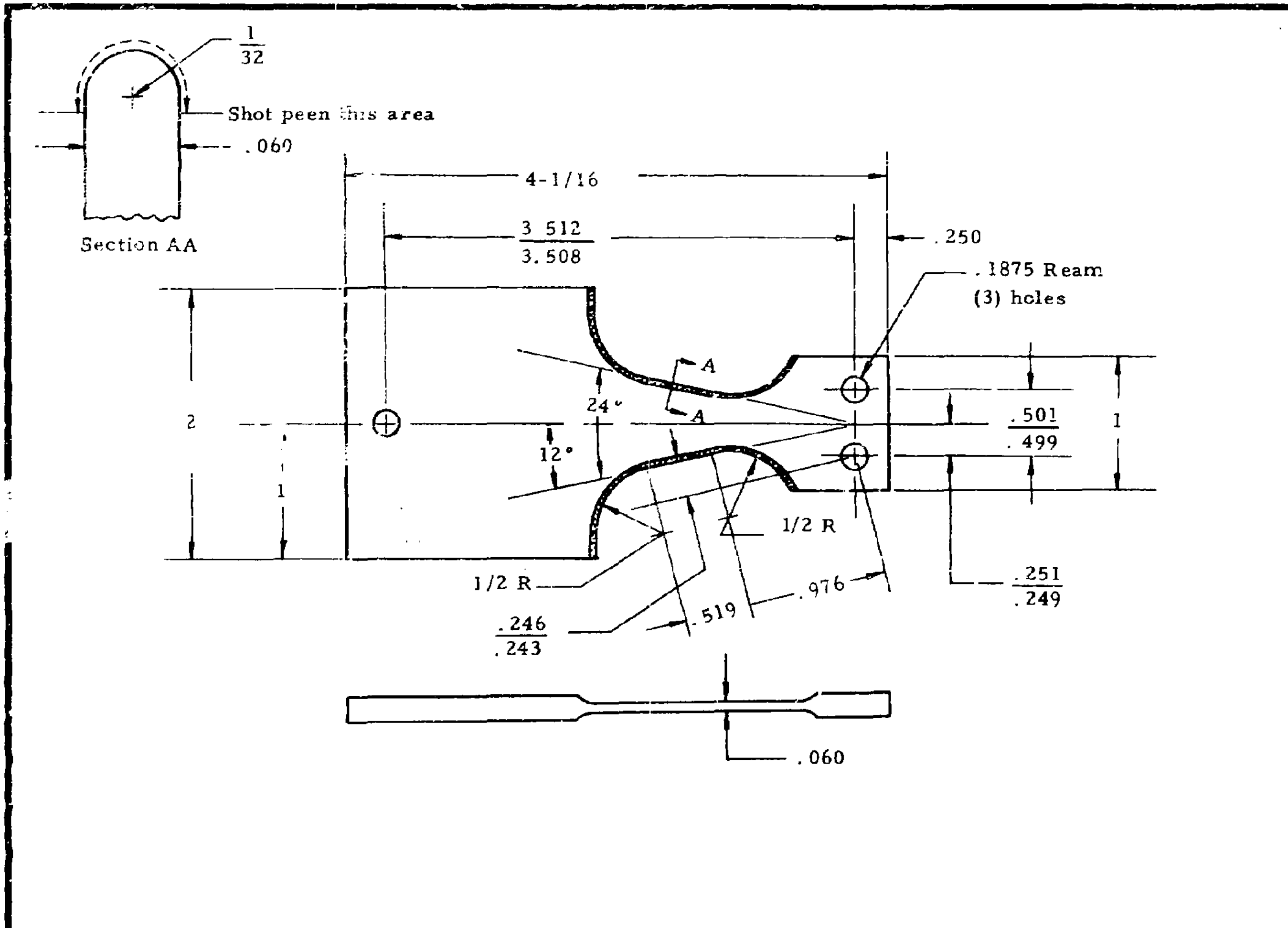


Figure 8
HIGH CYCLE FATIGUE SPECIMEN - TURNING, EDM, and ECM

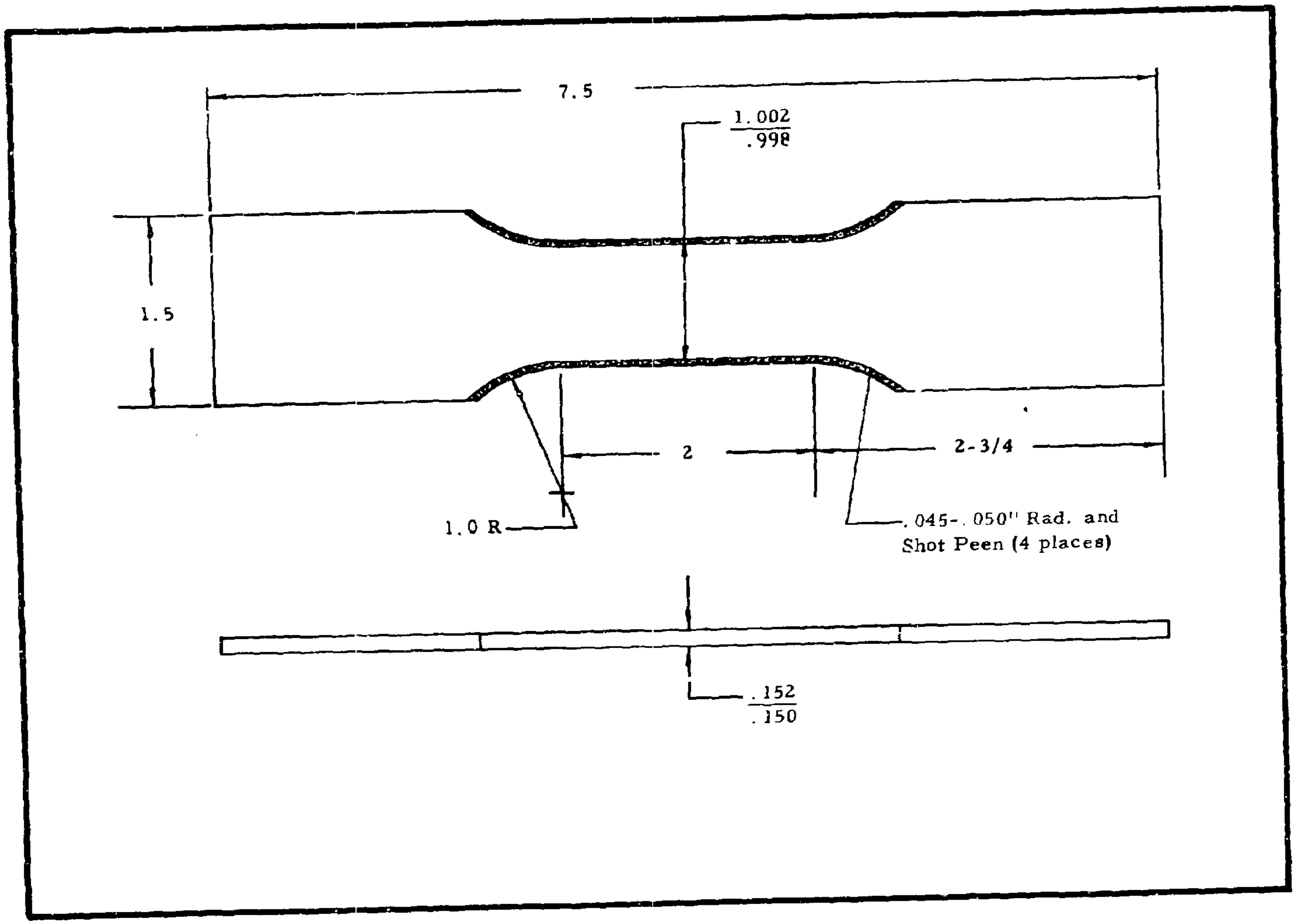


Figure 9
LOW CYCLE FATIGUE SPECIMEN - *GRINDING AND MILLING*

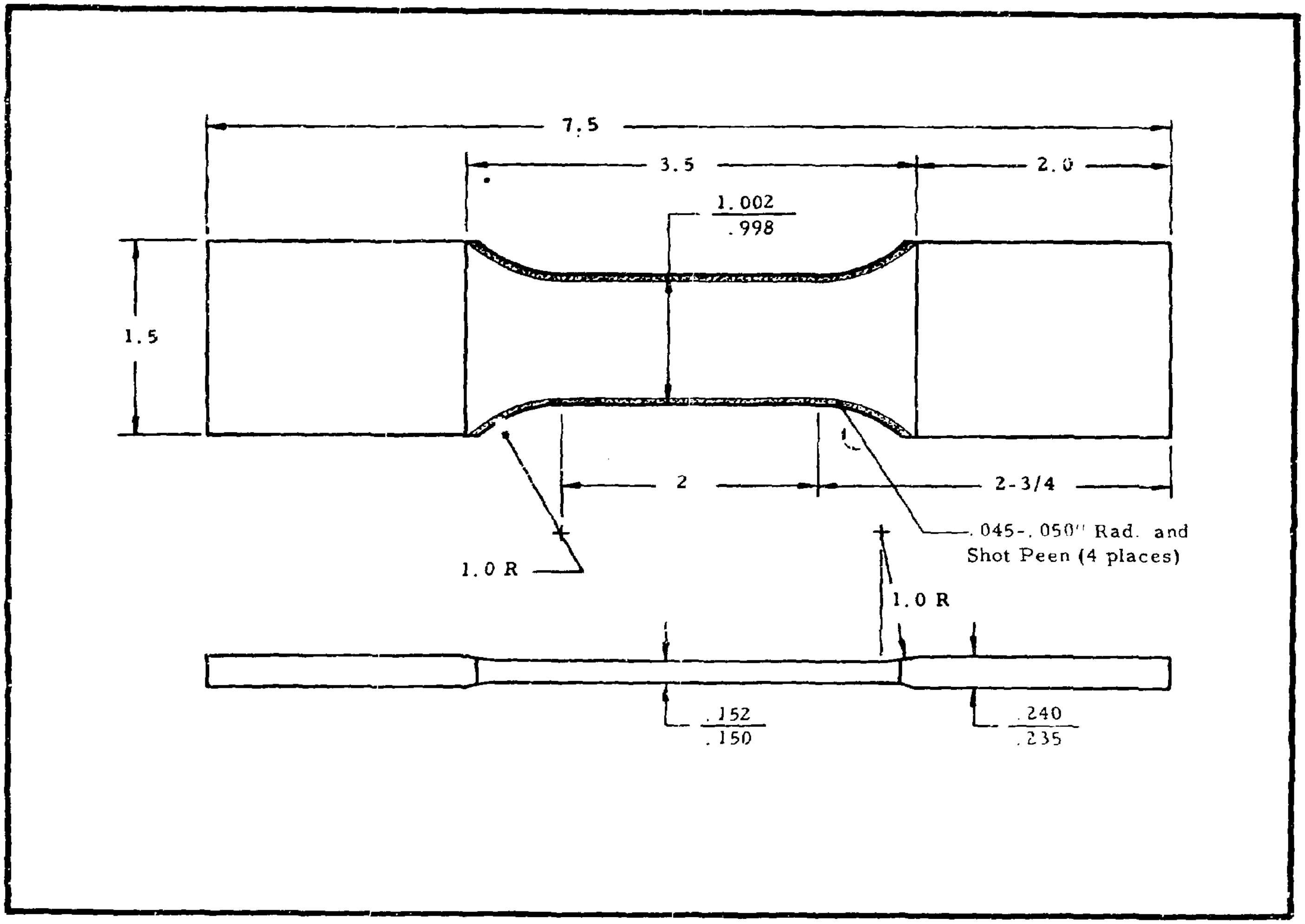


Figure 10
LOW CYCLE FATIGUE SPECIMEN - TURNING, EDM, and ECM

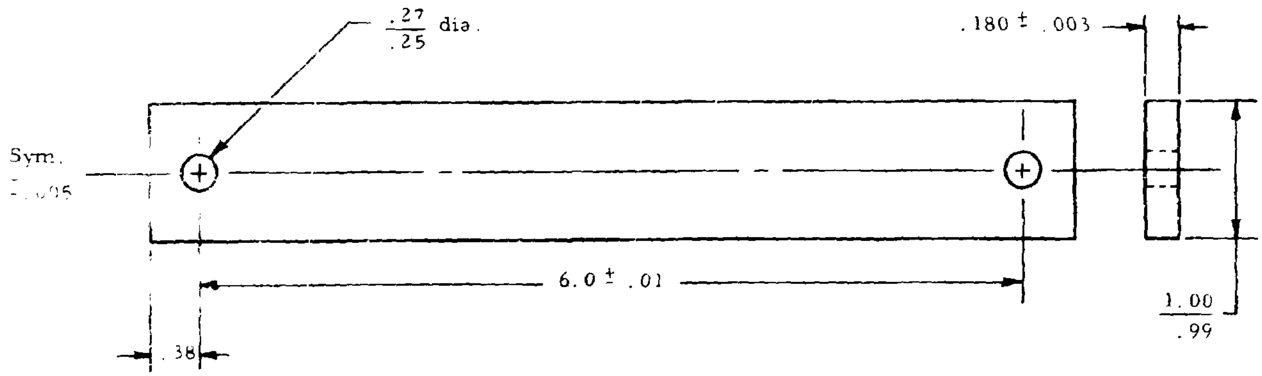


Figure 11
STRESS CORROSION SPECIMEN

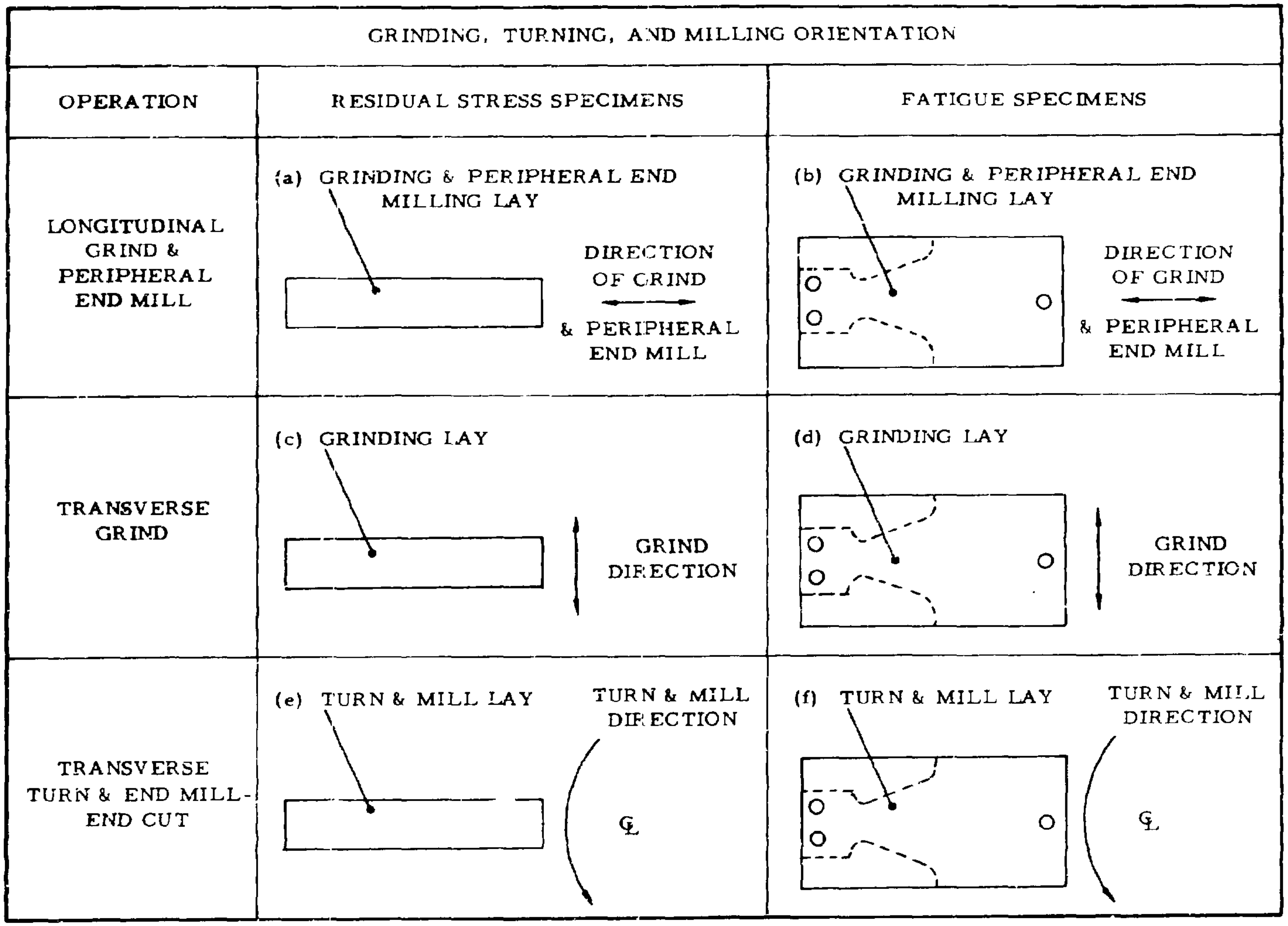


Figure 12
GRINDING, TURNING, and MILLING ORIENTATION ON SPECIMENS

5.4 Evaluation Procedures

In carrying out this program, studies of metallography, residual stress profiles, high cycle fatigue, low cycle fatigue and stress corrosion were used. A brief description of each is noted below.

Metallography

This phase consisted of preparing metallographic samples obtained from test coupons, ends of residual stress coupons, and unused portions of fatigue test specimens. These were examined at 1000X to determine the extent of microstructural alterations present. Detailed microhardness measurements were also made to characterize the surface condition. Standard stylus surface finish readings, reported in microinches AA were also included as a part of each characteristic surface study. Details of the metallographic procedure used are summarized in Appendix II-1.

A sampling of scanning electron photomicrographs and Talysurf traces were also taken on some of the surfaces. This was done to briefly explore the extent to which these tools might be used to further the understanding of surface integrity phenomena. Examples of the results of this effort are included in Section 6.13 of this report.

Measurement of Residual Stress

Residual stress profiles were determined for all of the significant alloy/material removal combinations studied. This work was done by the surface layer removal technique, following the same general procedures as were used and reported on previously. Details of this procedure are summarized in Appendix II-2.

High Cycle Fatigue Testing

The high cycle fatigue tests were run in the cantilever bending mode under constant force conditions in the range of 1800-2000 cycles per minute. All tests were run under fully reversed loading. The majority of tests were run at room temperature, although selected surface conditions were evaluated at an elevated temperature typical of the service temperature range for the particular alloy involved.

General Electric performed high cycle fatigue tests on AF 95, while Metcut performed these tests on all other materials. The specific test details are covered in Appendix II-3.

5.4 Evaluation Procedures (continued)

Low Cycle Fatigue Testing

Low cycle fatigue tests were accomplished in fully reversed bending at approximately 15 cycles per minute. The equipment used by Metcut and by General Electric for doing this work was different in design but closely equivalent in net cyclic loading effect on the specimens being tested. General Electric performed low cycle fatigue tests on AF 95, while Metcut performed tests on all other materials. For reasons noted above, low cycle fatigue tests were also carried out at both room temperature and elevated temperature. Details of these testing procedures are contained in Appendix II-4.

In evaluating low cycle fatigue tests, data are plotted as alternating pseudo stress versus total number of bending cycles which a specimen withstood prior to failure. Pseudo stress is an engineering term used in low cycle fatigue and is defined as the product of elastic modulus and the alternating strain of the specimen. The pseudo stress value will be higher than the actual stress in the alloy based on the bending moment in the specimen whenever the yield strength of the material is exceeded.

Stress Corrosion Testing

Stress corrosion testing was carried out on selected ferrous alloys using the salt fog exposure of bent beam specimens. This work was carried out by the Boeing Company in accordance with details contained in Appendix II-5.

6. SUMMARY OF RESULTS

6.1 AISI 4340 Steel, (Quenched and Tempered, 50 R_c)

The surface integrity behavior of this alloy was covered in considerable detail in the final report on the previous surface integrity contract, AFML-TR-70-11. Fatigue behavior developed in that program are included in this report for comparative purposes in Figure 13. As can be seen in referring to the groups of bar graphs shown in this figure, conventional and abusive grinding both caused a significant depression in high cycle fatigue strength as compared to gentle grinding. It can also be seen that shot peening in most cases had the effect of increasing fatigue strength considerably, although peening was not effective in fully erasing adverse effects due to abusive machining practices. Gentle grinding has been used as a base line to which other metal removal processes are compared, as shown in Figure 13 and throughout this report. The endurance limit of 102 ksi associated with gentle grinding is higher than that exhibited for all other metal removal processes. In some cases, however, a post-peening operation caused the fatigue strength to be elevated above the 102 ksi level.

Details of the surface integrity behavior of AISI 4340 are contained in the following parts of this section.

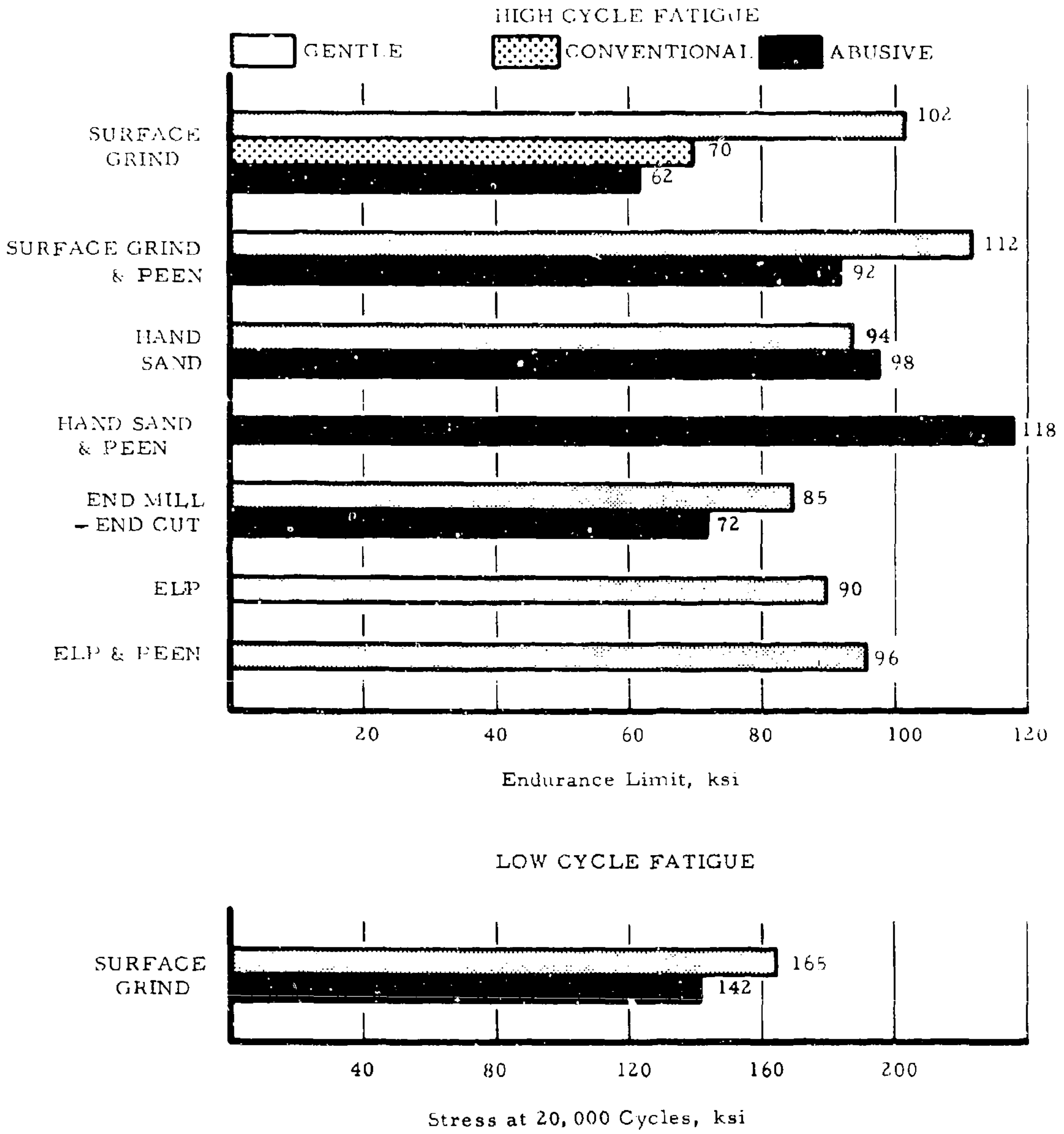


Figure 13
SUMMARY OF FATIGUE BEHAVIOR
OF AISI 4340 (QUENCHED & TEMPERED, 50 R_c)

6.1.1 Surface Grinding - AISI 4340 Steel, Q & T, 50 R_C

Metallography

The metallography of ground surfaces of AISI 4340 is very typical of that of martensitic ferrous alloys. If such a steel is heated to a temperature roughly in the range of 1500-1700° F, the solid state microstructure immediately changes from a mixture of ferrite or pearlite plus iron carbide to austenite. As soon as the heat source is removed, the temperature drops rapidly usually resulting in a transformation of this austenite to a hard brittle phase known as martensite. If the steel being heated rapidly is already in the martensitic state, the austenite-martensite cycle is simply repeated. This reaction will occur within an extremely short time cycle. Metal cutting operations which produce high localized heating for only extremely short periods of time will cause this austenite-martensite reaction to occur in a very shallow surface layer. This reaction is the basis of the majority of the surface effects seen in ferrous martensitic alloys. This would apply to AISI 4340 as well as 4340 modified, which is also included in the present report.

The metallographic studies of ground 4340 surfaces shown in Figure 14 as well as the following residual stress data, Figure 15 are based on studies completed prior to this contractural effort. They are included in this report, however, in order to document the conditions of the alloy which was covered by low cycle fatigue testing performed in connection with this contract. As can be seen in Figure 14, gentle grinding produced no visible surface alterations. This is typical of gentle or low stress grinding operations applied to martensitic steels. Conventional grinding as shown in Figure 14 (b) shows a small patch of hard untempered martensite (UTM), a light etching surface layer. Immediately beneath this patch is a softened subzone of over-tempered martensite (OTM). In the case of the abusively ground samples, Figure 14 (c), a thick layer of light etching untempered martensite was formed. It had sufficient depth to permit measurement of its hardness at 60 R_C. Not only is this UTM about 10 R_C points harder than the base metal, but since it is untempered, it is brittle and prone to cracking. Notice also that the hardness of the area immediately beneath the UTM is 46 R_C, somewhat softer than the base metal. This condition is a result of

6.1.1 Surface Grinding - AISI 4340 Steel, Q & T, 50 R_c (continued)

Metallography (continued)

overtempering the metal because of the high localized surface heating. The temperature in this overtempered region, however, did not get quite high enough during the grinding operation to form untempered martensite.

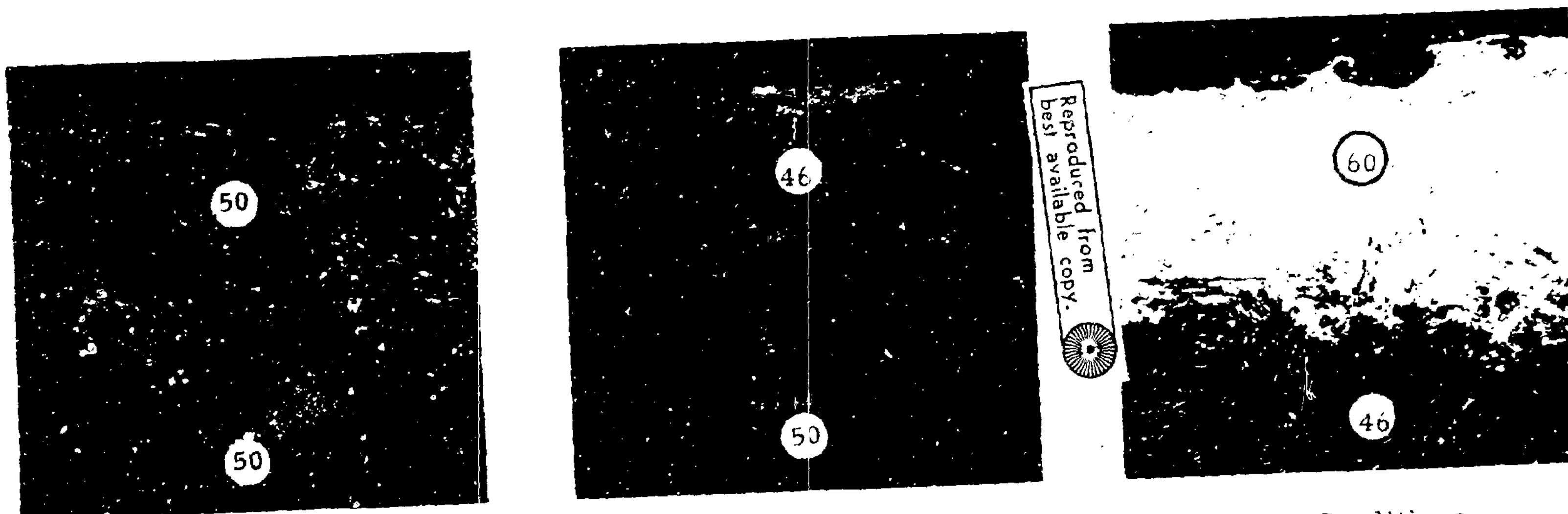
Residual Stress

Residual stress previously determined for ground 4340 at 50 R_c is shown in Figure 15. This chart shows that gentle grinding results in relatively low level residual stresses and in this case, shows a peak stress of approximately 25 ksi in compression. Both conventional and abusive grinding exhibited relatively high tensile residual stresses. In the case of this alloy, the peaks are in the range of 100 ksi. This is typical behavior as is the fact that the conventional grinding usually results in somewhat shallower stresses than abusive grinding, although the magnitude of the peaks are similar.

Low Cycle Fatigue Strength

Low cycle fatigue behavior conducted in accordance with the details of Appendix II-4 at room temperature is summarized in Figure 16. As can be seen in Figure 16, the stress which AISI 4340 withstood for 20,000 bending cycles was reduced from 165 to 142 ksi by shifting from gentle to abusive grinding. This is a 14 percent drop in stress associated with equal lives of 20,000 cycles. In another comparison, at the constant stress of 165 ksi, it may also be seen that the cyclic life was reduced from 20,000 to 12,500 cycles by shifting from gentle to abusive grinding. This is a 38 percent loss in cyclic life at a fixed stress.

While the magnitude is somewhat different, it is evident that abusive grinding causes a depression in low cycle fatigue behavior in this alloy roughly in proportion to that previously determined for the high cycle fatigue behavior of the same material. Low cycle fatigue data are summarized in Table XIII.



(a) Gentle Conditions
Surface Finish:
Perpendicular to lay: 45 AA
Parallel to lay: 10 AA

(b) Conventional Conditions
Surface Finish:
Perpendicular to lay: 40 AA
Parallel to lay: 10 AA

(c) Abusive Conditions
Surface Finish:
Perpendicular to lay: 50 AA
Parallel to lay: 15 AA

Gentle grinding produced no visible surface alterations. Conventional grinding shows evidence of spotty surface rehardening and underlying overtempering or softening. Abusive grinding produced a rehardened surface layer averaging .001" deep and an underlying overtempered zone approximately .004" deep. Indicated hardness data are R_c values converted from Knoop microhardness measurements. Surface finish measurements are averages of readings made on all specimens from each group.

Magnification: 1000X

ORIENTATION: LONGITUDINAL GRIND. SURFACE SECTIONS PERPENDICULAR TO GRINDING LAY.

Figure 14
SURFACE CHARACTERISTICS OF AISI 4340 (QUENCHED AND TEMPERED, 50 R_c) PRODUCED BY SURFACE GRINDING

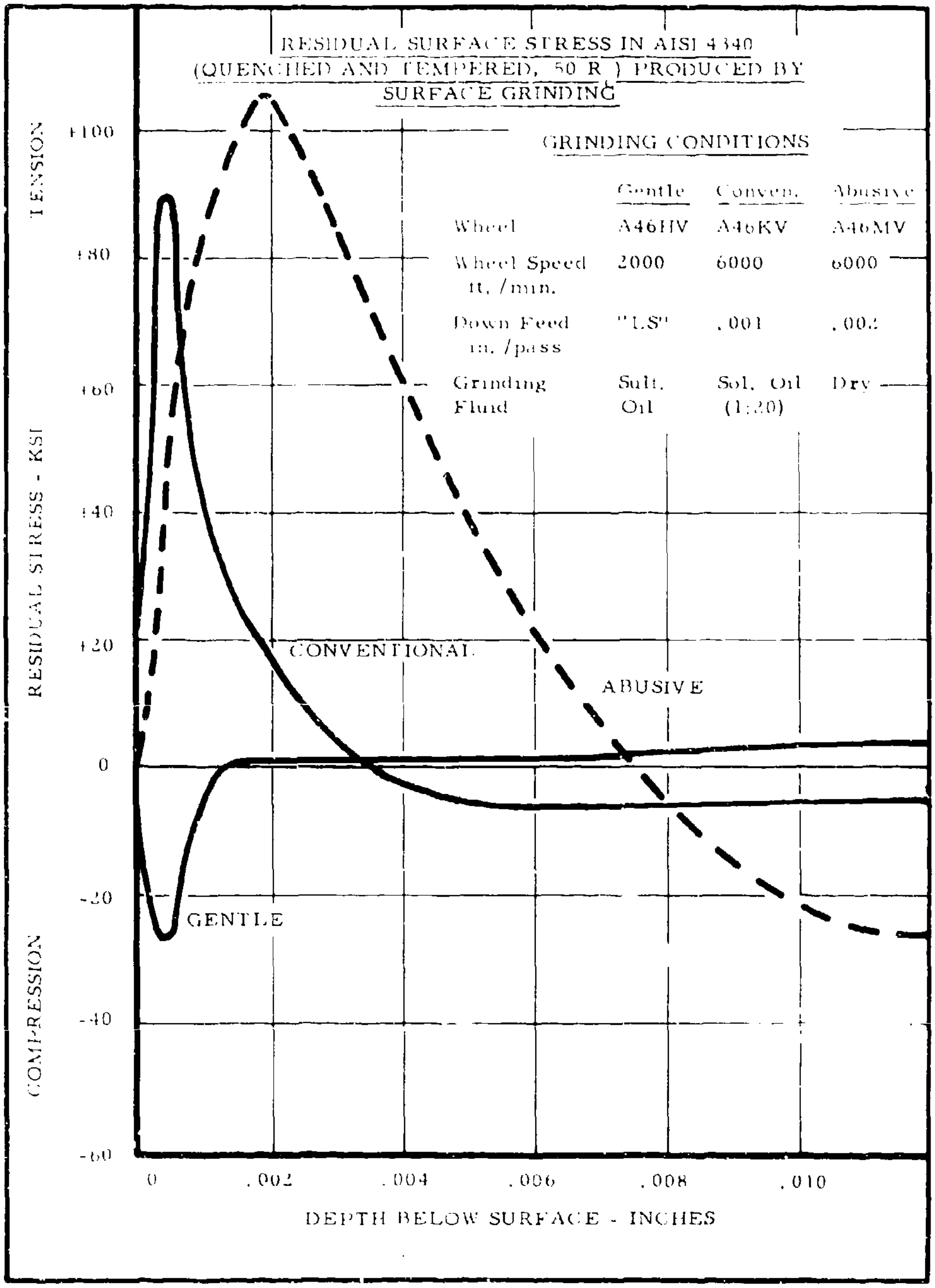


Figure 15
RESIDUAL STRESS IN AISI 4340: SURFACE GRINDING

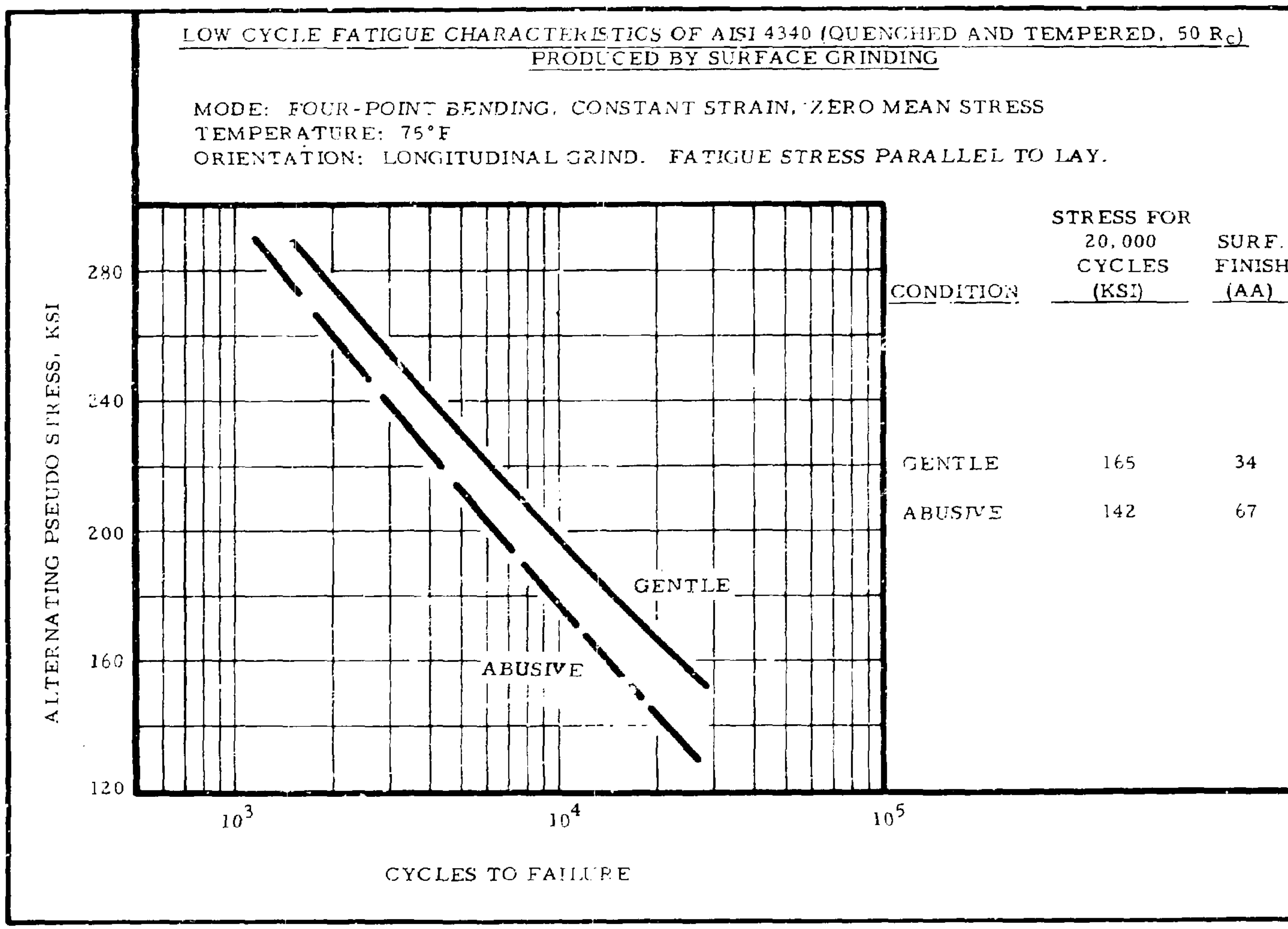


Figure 16
LOW CYCLE FATIGUE OF AISI 4340: SURFACE GRINDING

6.1.2 End Milling-End Cutting - AISI 4340 Steel, Q & T, 50 R_c

Metallography

Photomicrographs showing the types of surfaces produced by transverse end milling (end cutting) 4340 steel at 50 R_c are shown in Figure 17. The surfaces illustrated are perpendicular to the cutting tool path. Note the presence of some laps or folds loosely adherent to the surface, particularly in the case of the gently cut samples, Figure 17 (a). Notice also in the abusively milled samples, Figure 17 (b), the formation of the altered surface layers consisting of a light etching band approximately .0001 in. deep and an underlying darkened band in the range of .0001 to .0002 in. deep. Microhardness measurements on the abusively milled sample were able to detect surface softening to 46 R_c associated with the darkened layer of overtempered martensite. The hardness of the white untempered surface layer was probably in excess of 60 R_c. Because of the shallowness of this white layer, its hardness could not be measured by available techniques. The same microstructural situation may exist in the gently milled sample, Figure 17 (a), although the layers are much thinner. The hardness levels of these layers could not be measured. These surface reactions are typical of those found in quenched and tempered martensitic steels under metal removal conditions where high localized heating occurs at the surface.

Residual Stress

Residual stress profiles in these samples, produced by transverse milling, showed that both gentle and abusive milling produced a predominant peak compressive stress of approximately 120 ksi. The abusive condition also exhibited a superficial peak tensile stress of 300 ksi, although the depth affected was very small. These data are plotted in Figure 18.

As can be seen from this plot, the peak stress due to gentle cutting occurs at a depth of approximately .001 in. and shows a total affected depth of about .008 in. In the abusively milled sample, however, the overall compressive effect was much greater. The compressive peak occurred at .004 in. and the total affected surface layer is probably in excess of .012 in.

6.1.2 End Milling- End Cutting - AISI 4340 Steel, Q & T, 50 R_c (continued)

Residual Stress (continued)

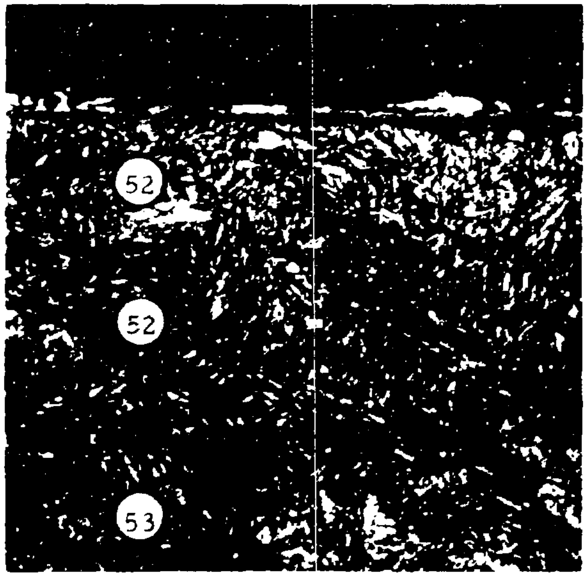
Even though peak residual stress levels are similar, greater distortion was produced in the abusively milled sample because of the greater surface volume which is residually loaded in compression Because the compressive zone lies under the shallow tensile zone in the abusively produced surface and is much deeper overall, the compressive condition is believed to predominate in the integrity characteristics of this surface.

High Cycle Fatigue Strength

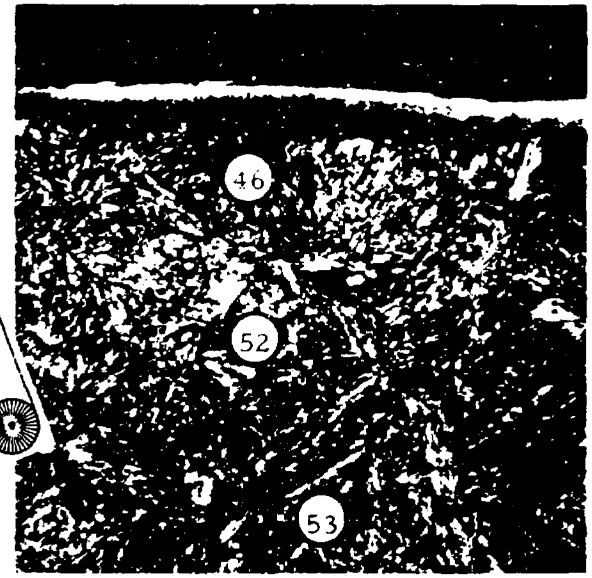
A summary of the fatigue behavior of gentle versus abusively milled 4340 is shown in Figure 19. The endurance limit attributable to gentle milling is 85 ksi, compared to 72 ksi associated with the abusively milled condition. The surface finishes of each group were essentially the same, in the 70 to 75 ksi range. The difference in fatigue behavior is apparently due to the presence of overtempered martensite in the abusively milled surface. As indicated in Figure 17, hardness of the gently versus abusively cut surfaces were 52 versus 46 R_c. This lower hardness, due to localized surface heating, is roughly proportional to fatigue strength. These samples were finished with transverse milling, hence the fatigue stress was applied perpendicular to the surface lay. Fatigue data are summarized in Table XII.

Stress Corrosion

A few samples of 4340 finished by both gentle and abusive conditions were subjected to stress corrosion testing. All samples failed in the range of approximately 40 to 150 hours and in such a pattern as to provide inconclusive data regarding stress corrosion behavior. The limited data available are summarized in Table XXVIII.



(a) Gentle Milling
Surface Finish:
Perpendicular to lay: 75 AA
Parallel to lay: 15 AA



(b) Abusive Milling
Surface Finish:
Perpendicular to lay: 71 AA
Parallel to lay: 12 AA

Thin layers of surface alteration are evident. Figure (a) shows several loosely adherent grinding particles adjacent to the surface and with a very thin altered surface layer. Abusive milling shows a typical surface layer consisting of untempered martensite (light etching) and a subsequent band of overtempered martensite. The diffuse appearance of the surface layers is because of the high level of plastic deformation also produced in this surface by the cutting action. Indicated hardness data are R_c values converted from Knoop microhardness measurements.

Magnifications: 1000X

ORIENTATION: TRANSVERSE MILL. SURFACE SECTIONS PERPENDICULAR TO LAY.

Figure 17
SURFACE CHARACTERISTICS OF AISI 4340 (QUENCHED AND TEMPERED, [illegible] R_c)
PRODUCED BY END MILLING - END CUTTING

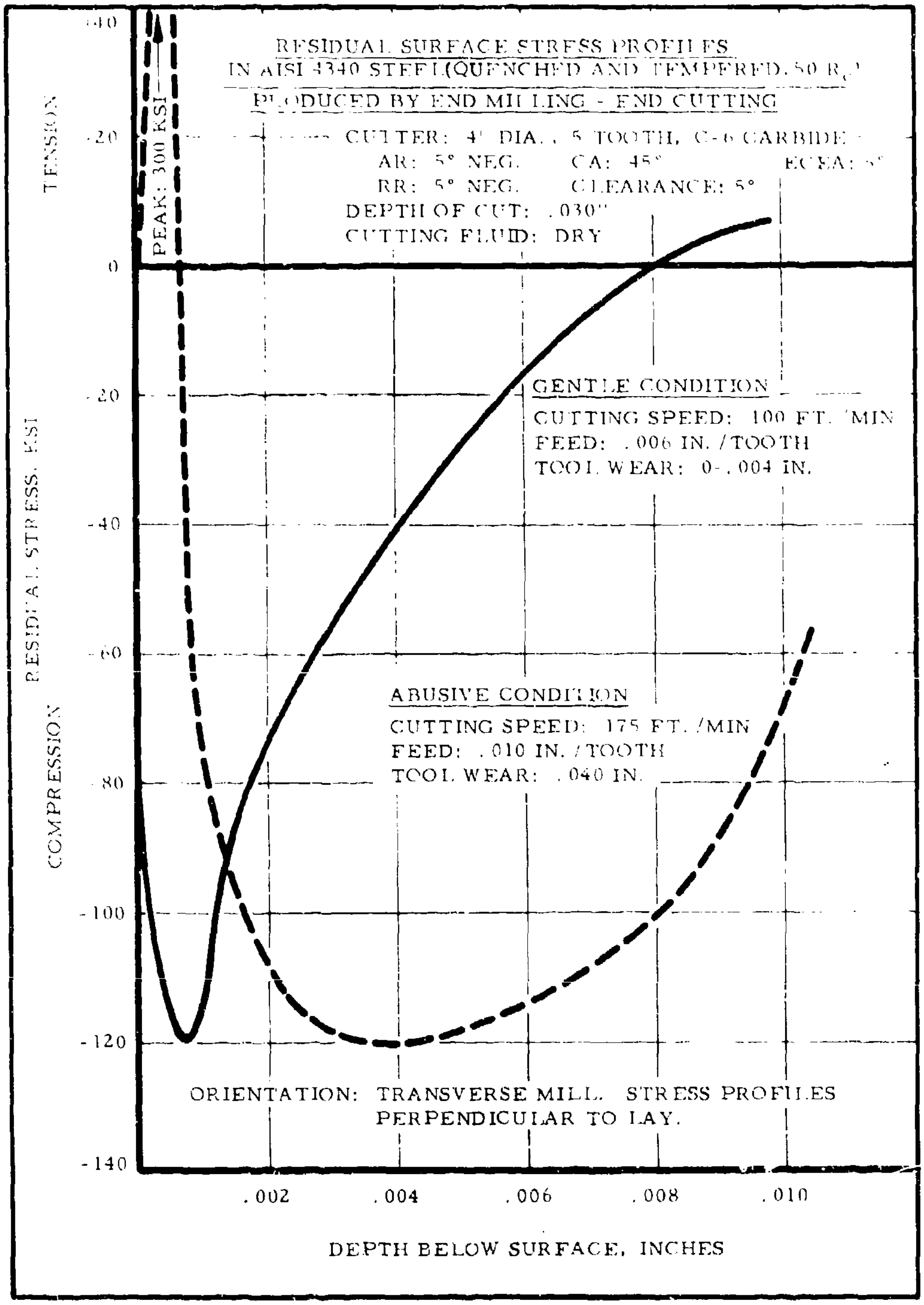


Figure 18
RESIDUAL STRESS IN AISI 4340: END MILLING - END CUTTING

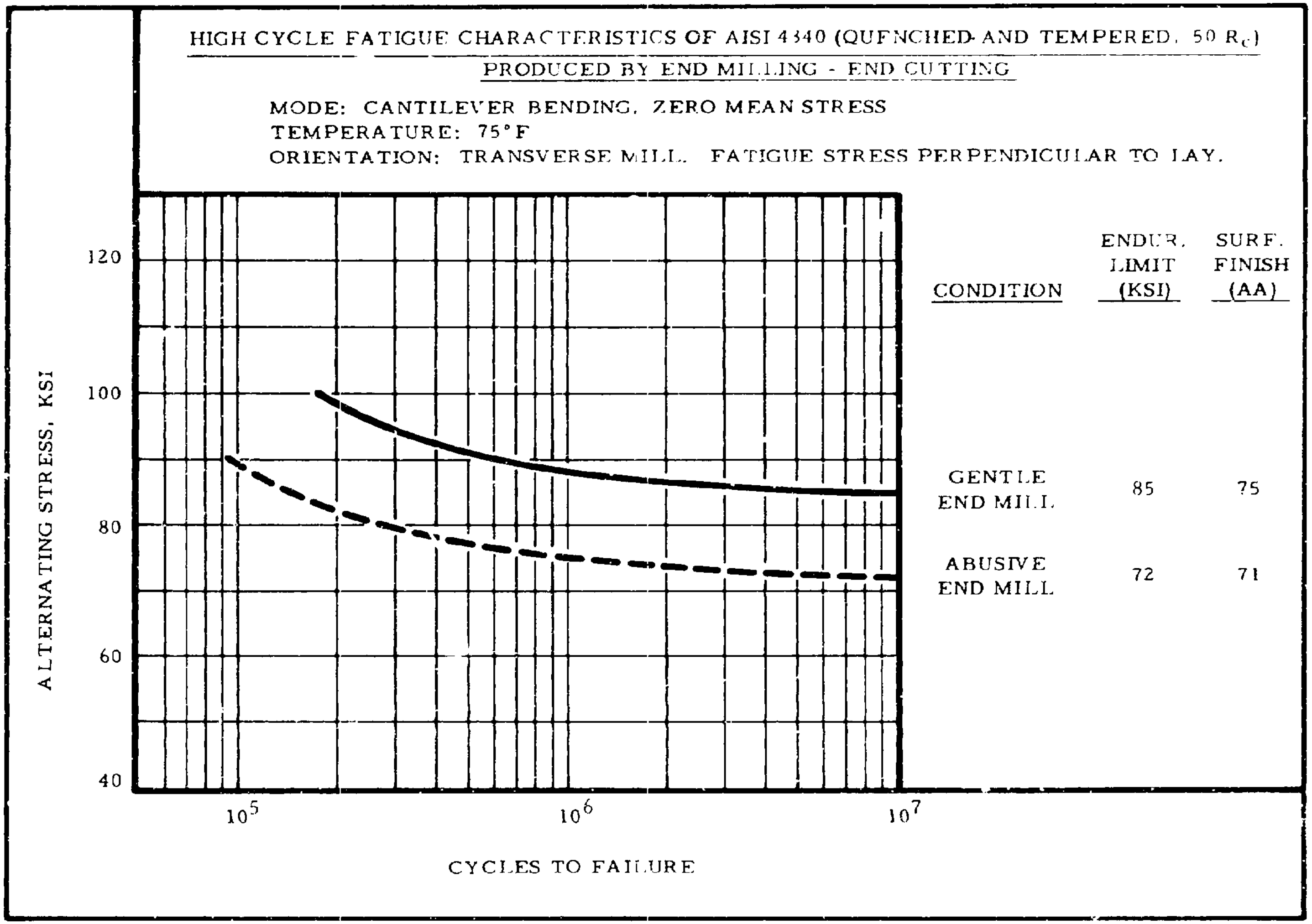


Figure 19
HIGH CYCLE FATIGUE OF AISI 4340: END MILLING - END CUTTING

6.2 AISI 4340 Steel Modified, Q & T, 53 R_C, 285 ksi

Surface integrity behavior of 4340 Modified has been evaluated on this alloy at a hardness level of 53 R_C to determine its relative behavior at this hardness level in comparison with that of AISI 4340 at a somewhat lower hardness. The AISI 4340 data is summarized in Section 6.1.

The fatigue data on 4340 Modified shown in Figure 20 indicates the same type of behavior as was previously exhibited for AISI 4340 (Figure 13). Most significant is the wide variation in fatigue strength associated with differences in surface grinding. Under gentle grinding conditions, an endurance limit of 122 ksi was obtained. As shown in Figure 20, the fatigue was depressed to the range of 62-65 ksi by abusive and conventional grinding. These abusive and conventional levels of 4340 Modified are essentially the same as that exhibited by AISI 4340 under the same grinding conditions. The fatigue strength resulting from gentle grinding is somewhat higher in the case of the 4340 Modified because of the higher strength to which the alloy was heat treated prior to testing. It is interesting to note, however, that all advantage afforded by the modified alloy in heat treating it to a higher strength level is lost in the event that surface damage is inflicted during grinding.

It is also worthy to note that hand disc sanding resulted in a relatively high endurance level of 105 ksi. Within the range of conditions studied, no significant surface damage was inflicted even under the abusive sanding conditions. In general, hand sanding has been shown to produce relatively high levels of surface integrity under all conditions studied when applied to various alloys.

End milling used to perform an end cutting operation resulted in a somewhat depressed endurance limit; namely, 63 ksi. Here again both gentle and abusive end milling resulted in the same fatigue which was characteristic of the level resulting from abusive grinding.

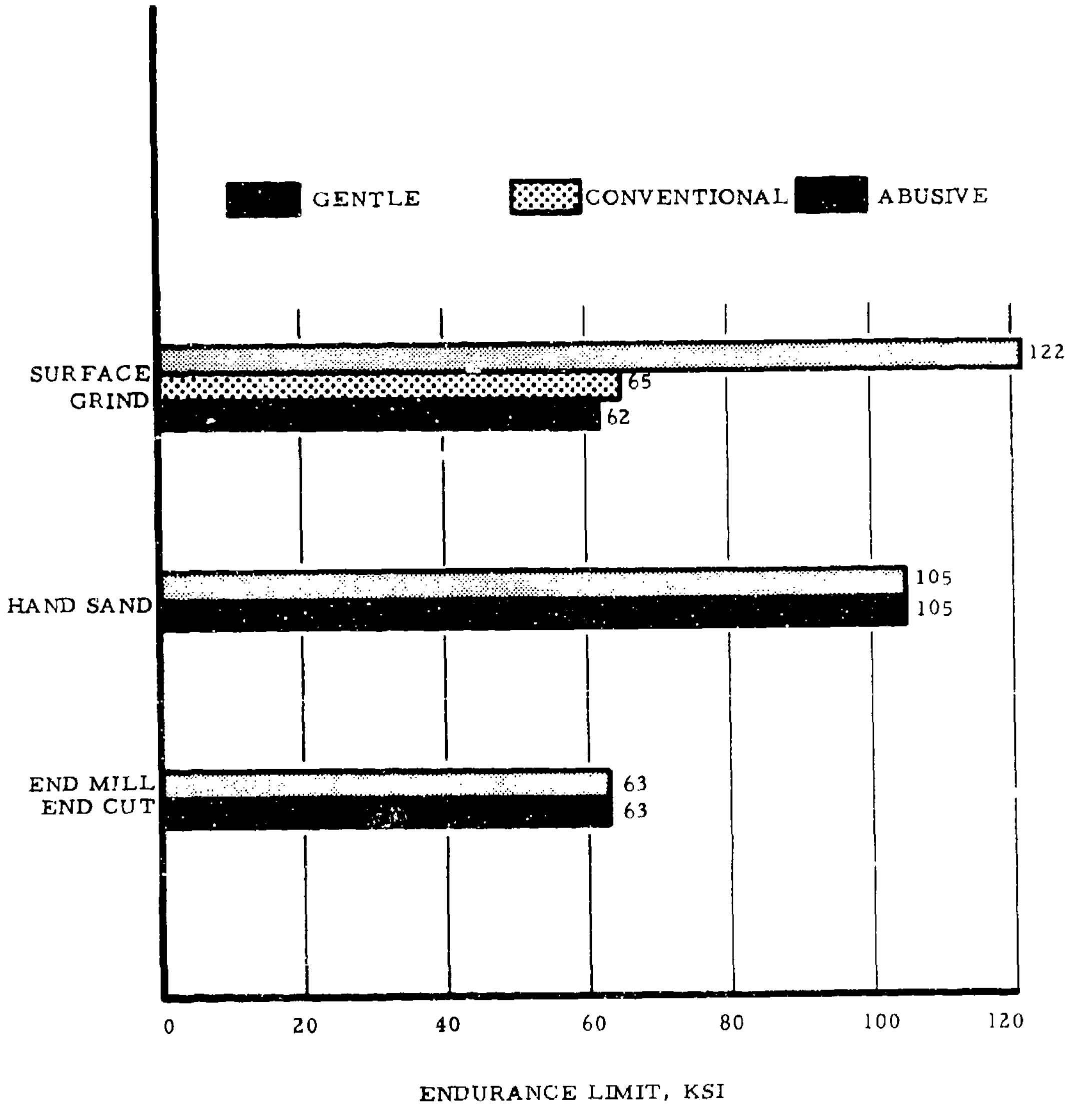


Figure 20

SUMMARY OF HIGH CYCLE FATIGUE BEHAVIOR
OF 4340 MODIFIED (QUENCHED AND TEMPERED, 53 R_c, 285 KSI)

6.2.1 Surface Grinding - AISI 4340 Modified, Q & T, 53 R_c, 285 ksi

Metallography

Photomicrographs of structures produced by gentle, conventional, and abusive grinding on 4340 Modified are shown in Figure 21. Grinding conditions are summarized in Table II. In keeping with the procedure used for the standard data set evaluation, the conditions to produce the various levels of grinding severity were selected so as to attain approximately equal surface finish levels. In the case of gentle grinding, no surface alterations or significant microhardness changes are evident. Both the conventional and abusive grinding procedures, however, produce significant amounts of untempered martensite on the surface. The underlying layer of overtempered martensite, typical of that found in martensitic steels, is also present. It appears to be slightly less predominant, however, than was observed in AISI 4340. A comparison of Figure 21 with Figure 14 indicates, by the quantities of UTM present, that the 4340 Modified at this hardness level of approximately 53 R_c appears to be somewhat more sensitive to grinding damage than AISI 4340 at 50 R_c.

Residual Stress

Residual stress profiles produced in 4340 Modified are shown in Figure 22. For comparison with 4340 at 50 R_c ground under equivalent conditions, the following data are presented.

Grinding Condition	Peak Residual Stress, ksi	
	4340 Modified, 53 R_c	AISI 4340, 50 R_c*
Gentle	60, compression	25, compression
Conventional	150, tension	90, tension
Abusive	300, tension	105, tension

These data would again suggest that martensitic steels show increased sensitivity to surface damage during grinding as the hardness level is increased.

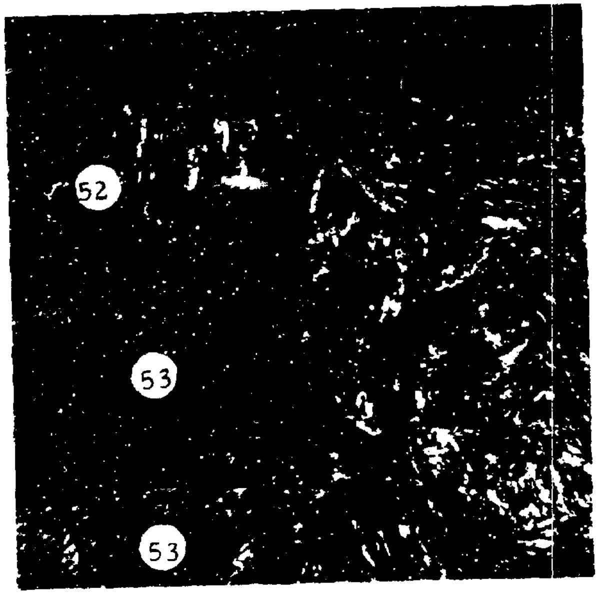
* Contract F33615-68-C-1003 (Report No. AFML-TR-70-11)

6.2.1 Surface Grinding - AISI 4340 Modified, Q & T, 53 R_C, 285 ksi (continued)

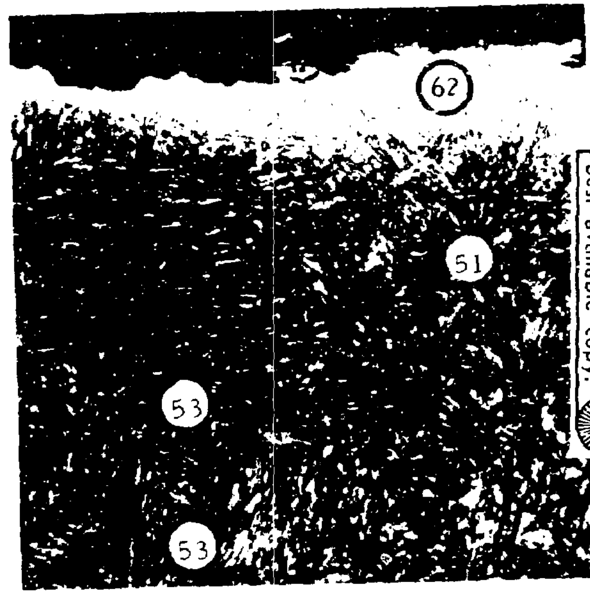
High Cycle Fatigue Strength

Fatigue strengths obtained on samples of 4340 Modified are shown in Figure 23. Gentle grinding exhibited an endurance limit of 122 ksi. Conventionally and abusively ground samples yielded 65 and 62 ksi, respectively. These are comparable to data previously developed for 4340 at 50 R_C in which the gentle, conventional, and abusive strengths were 102, 70, and 62 ksi, respectively.* The higher fatigue strength of the gently ground 4340 Modified (122 versus 102 ksi) is logically associated with the higher strength level to which this alloy had been heat treated. The lower fatigue strengths in the 65 ksi range, however, appear to be typical of these alloys when untempered and overtempered martensite are present in the surface.

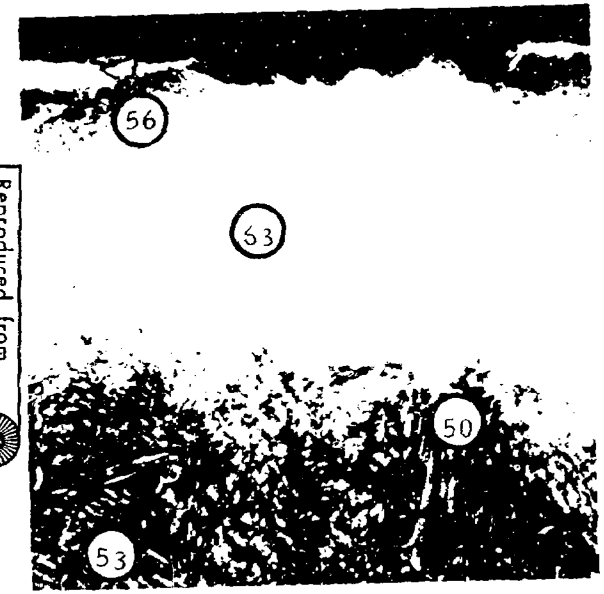
* Contract F33615-68-C-1003 (Report No. AFML-TR-70-11)



(a) Gentle Grinding
Surface Finish:
Perpendicular to lay: 25 AA
Parallel to lay: 15 AA



(b) Conventional Grinding
Surface Finish:
Perpendicular to lay: 50 AA
Parallel to lay: 26 AA



(c) Abusive Grinding
Surface Finish:
Perpendicular to lay: 37 AA
Parallel to lay: 20 AA

The typical response of martensitic steels to surface grinding is illustrated above. Gentle grinding shows no surface alterations. Conventional grinding shows evidence of substantial untempered martensite formation (light etching area). The quantity of untempered martensite in this sample is considerably more than is observed in martensitic steels at lower hardness levels. Abusive grinding exhibits extensive untempered martensite formation plus some surface cracking which again is typical. Hardness measurements are R_c values converted from Knoop readings. Surface finish measurements are averages of all the specimens made from each group.

Magnifications: 1000X

ORIENTATION: LONGITUDINAL GRIND. SURFACE SECTIONS PERPENDICULAR TO GRINDING LAY.

Figure 21
SURFACE CHARACTERISTICS OF 4340 MODIFIED, (QUENCHED AND TEMPERED, 53 R_c 285 KSI) PRODUCED BY SURFACE GRINDING

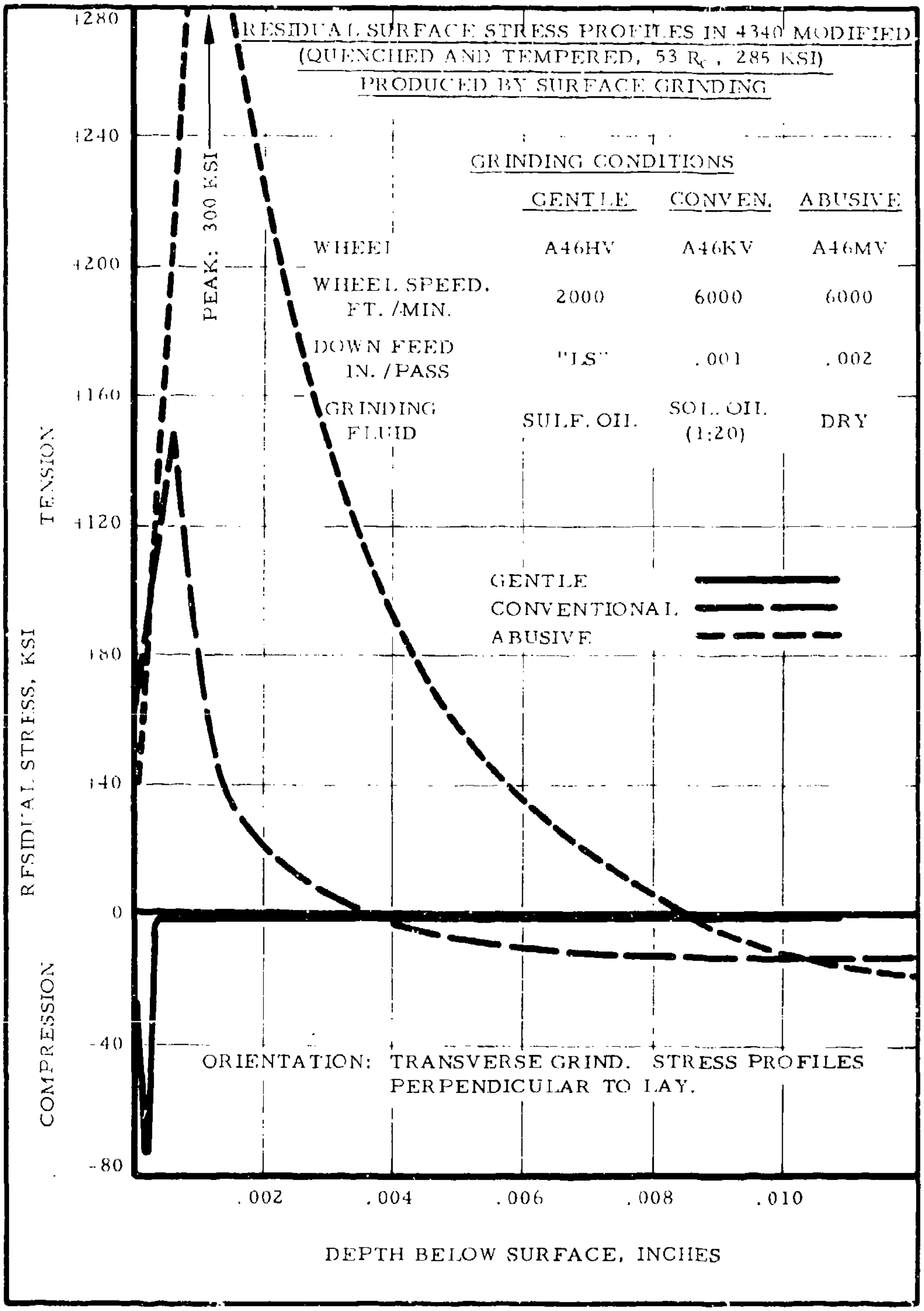


Figure 22
RESIDUAL STRESS IN 4340 MODIFIED: SURFACE GRINDING

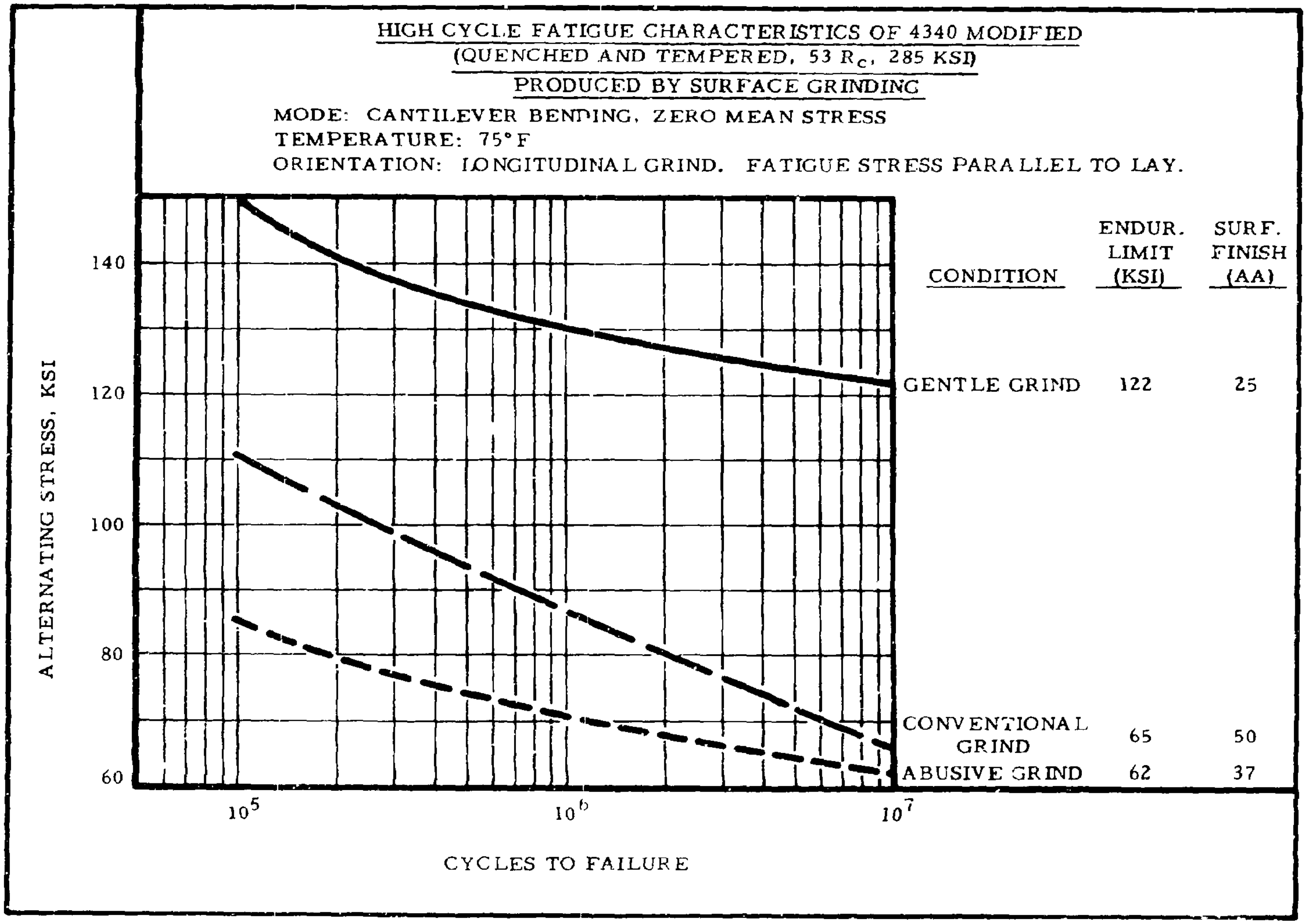


Figure 23
HIGH CYCLE FATIGUE OF 4340 MODIFIED: SURFACE GRINDING

6.2.2 Hand Sanding - AISI 4340 Modified, Q & T, 53 R_c, 285 ksi

Metallography

Photomicrographs of modified 4340 finished by hand disc sanding are shown in Figure 24. Gentle sanding shows no evidence of surface alterations. Abusive sanding shows a very thin light etching layer on the surface and a thin dark etching layer underneath suggesting the presence of untempered and over-tempered martensite. The layers are too thin, however, to permit any determination of microhardness changes.

Residual Stress

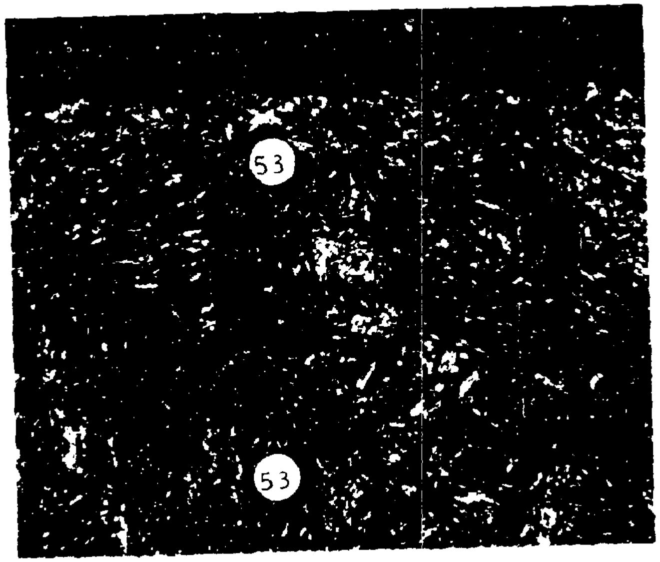
Residual stress profiles of 4340 modified as the result of gentle and abusive hand sanding are shown in Figure 25. Both types of sanding produced shallow relatively high level compressive stresses in the vicinity of 80-90 ksi, but with a total depth of .001" or less. This behavior is similar to that observed previously as a result of hand belt sanding on AISI 4340 in which case peak residual compressive stresses of 40 and 70 ksi were associated with gentle and abusive methods, respectively.

High Cycle Fatigue Strength

Fatigue strength of hand sanded samples resulted in an endurance limit of 105 ksi for both conditions (Figure 26). Since the photomicrographs revealed no significant surface alterations, and since residual stress distributions were quite similar, similar fatigue behavior can also be expected. As in the case of hand belt sanding previously performed on AISI 4340, both the gentle and abusive hand sanding conditions result in a fairly high surface integrity level. Fatigue data are summarized in Table XIV.

Stress Corrosion

A limited number of stress corrosion tests were run on disc sanded samples of 4340 Modified in accordance with details of Appendix II-5. All of the samples failed in relatively short times, however, making it difficult to draw meaningful conclusions from the data. Stress corrosion results are summarized, however, in Table XXVIII.



(a) Gentle Sanding
Surface Finish:
Perpendicular to lay: 10 AA
Parallel to lay: 10 AA

(b) Abusive Sanding
Surface Finish:
Perpendicular to lay: 15 AA
Parallel to lay: 15 AA

Micrographs of martensitic steel showing surfaces typical of a hand disc or sanding operation. Gentle sanding shows no evidence of surface alterations. The abusive sanding shows a very thin white band on the surface as well as from smearing or local build-up. No microhardness variations were observed as a result of either gentle or abusive sanding. The structure suggests that the abusive sanding produced extremely thin layers of untempered and overtempered martensite, but that they are too shallow to be measured. Indicated hardness data are R_C values converted from Knoop microhardness measurements. Surface finish measurements are averages of readings made on all specimens from each group.

Magnification: 1000X

ORIENTATION: TRANSVERSE SAND SURFACE SECTION PERPENDICULAR TO SANDING LAY.

Figure 24
SURFACE CHARACTERISTICS OF 4340 MODIFIED (QUENCHED AND TEMPERED, 53 R_C, 285 KSI) PRODUCED BY <u>HAND SANDING</u>

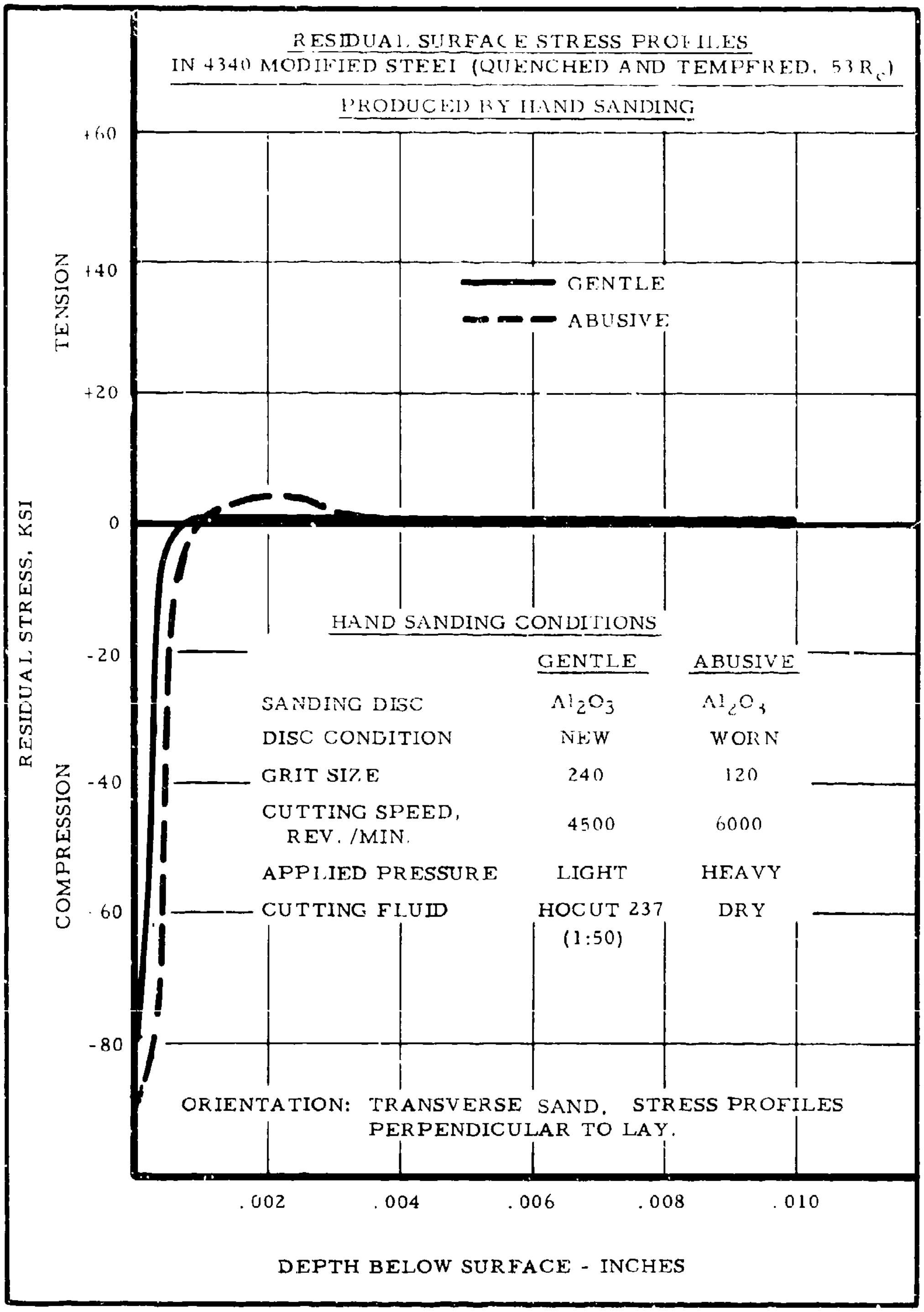


Figure 25
RESIDUAL STRESS IN 4340 MODIFIED: HAND SANDING

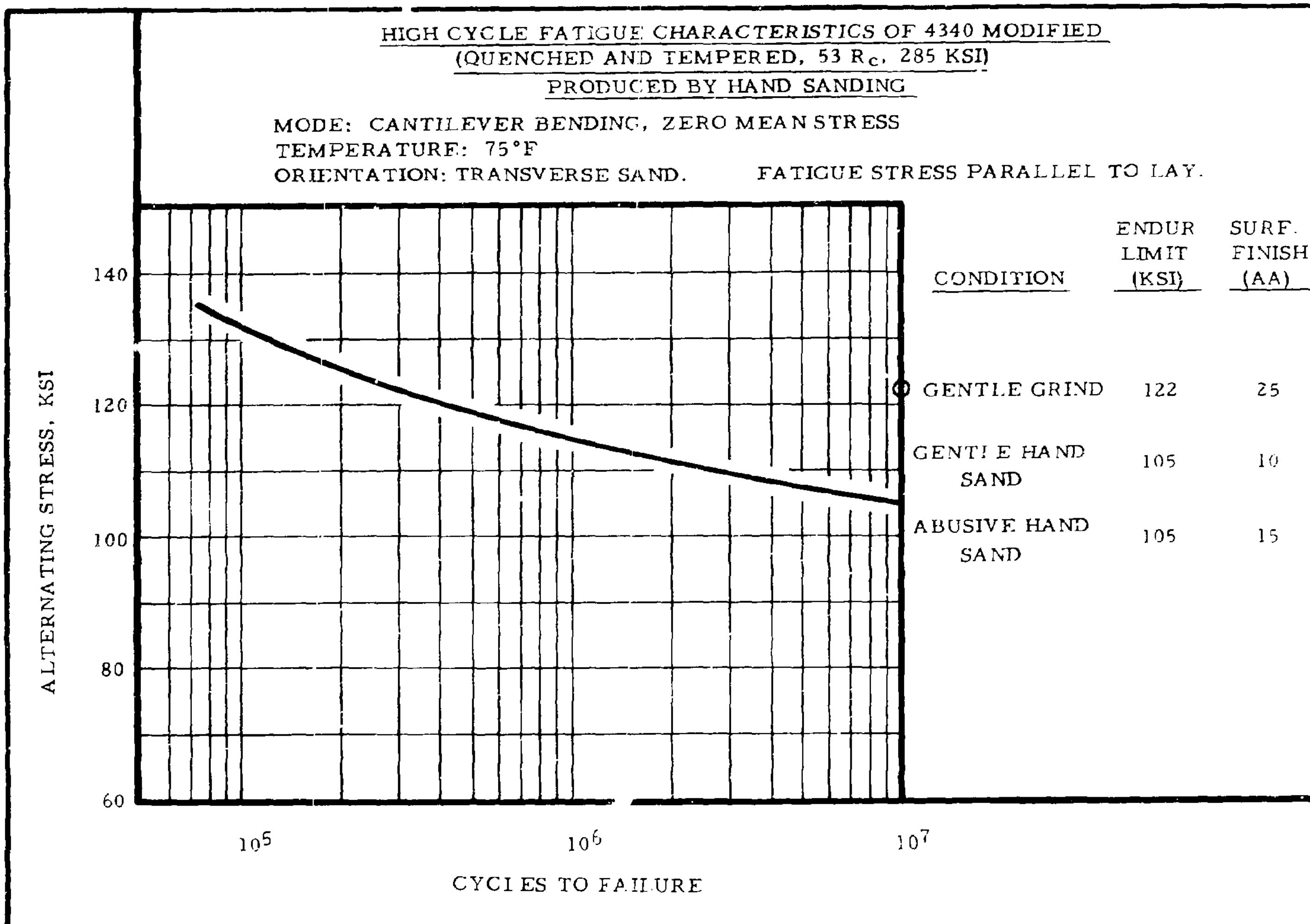


Figure 26
HIGH CYCLE FATIGUE OF 4340 MODIFIED: HAND SANDING

6.2.3 End Milling-End Cutting - AISI 4340 Modified, Q & T, 53 R_C, 285 ksi

Metallography

Photomicrographs of structures produced by gentle and abusive end milling-end cutting on 4340 Modified are shown in Figure 27. The milling conditions used for making the test cuts on these specimens are summarized in Table IV.

The cross section of the gently milled surface shows no evidence of plastic deformation or overheating. Microhardness data, however, indicate surface softening, averaging 6 points R_C. A maximum softening of 8 points R_C was consistently measured on one sample, .0005 in. beneath the surface.

The abusive milling condition produced a thin altered surface layer which is highly worked or deformed. Apparently, no untempered martensite is present in this surface as evidenced by the lack of a white surface layer. Microhardness measurements indicate that surface hardness changes are approximately the same as those found on the gently milled samples, although hardness losses as great as 10 R_C were found on one sample. A similar decrease in surface hardness was previously observed on the standard AISI 4340 analysis milled under similar cutting conditions, Section 6.1.2. In the case of the standard 4340, however, a thin surface layer of untempered martensite could be observed.

Residual Stress

Residual stress profiles produced in 4340 Modified using the milling conditions chosen for this program are shown in Figure 28. The gently milled sample shows peak surface compression of 40 ksi, while the abusively milled samples show peak surface compression of a much greater depth and approaching the stress level of 100 ksi. Stresses produced by the abusive milling condition penetrated to a much greater depth than those produced by gentle milling. These effects, namely stress level direction and relative depth, are similar to those which have been observed previously in milling several different alloys.

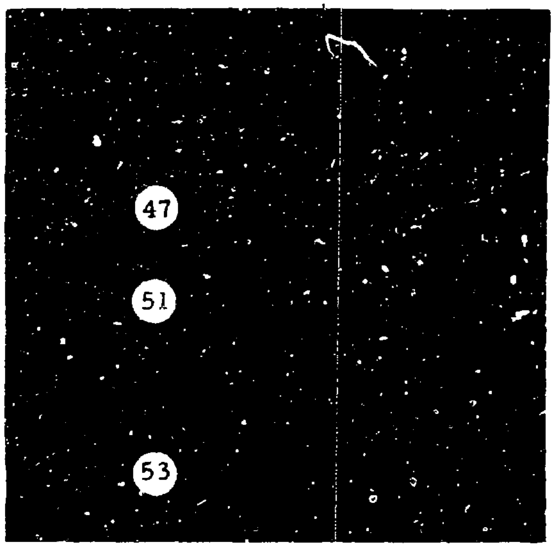
6.2.3 End Milling-End Cutting - AISI 4340 Modified, Q & T, 53 R_c, 285 ksi (continued)

High Cycle Fatigue Strength

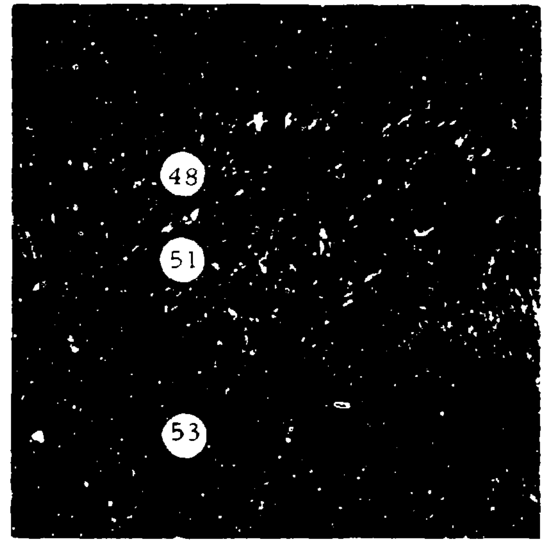
Fatigue strengths obtained in gently and abusively milled samples of 4340 Modified are shown in Figure 29. Both milling conditions result in a fatigue strength of approximately 63 ksi. These are relatively low values as compared to the fatigue strength of 122 ksi which results from gentle grinding on this alloy.

The relatively low fatigue strength exhibited by both milled samples is probably due to the presence of overtempered martensite in the surface layer. As indicated in Figure 27, both the gentle and abusive milling caused a hardness drop in the range of 3-4 points R_c. It is interesting to note that this fatigue depression occurs in the presence of overtempered martensite, even though relatively high compressive stresses are present in the sample. Note that in the case of abusive milling, a peak residual compressive stress of approximately 100 ksi performed no better in fatigue than the gentle milled sample which exhibited a peak compressive stress of 40 ksi. As has been shown in other instances while studying martensitic steels, the presence of overtempered (as well as untempered) martensite in the surface has an overriding effect in degrading fatigue properties.

A summary of the actual fatigue tests run on this material, which resulted in the curve shown in Figure 29, is included as Table XIV.



(a) Gentle Milling
Surface Finish:
Perpendicular to lay: 70 AA
Parallel to lay: 16 AA



(b) Abusive Milling
Surface Finish:
Perpendicular to lay: 33 AA
Parallel to lay: 8 AA

Gentle milling shows little evidence of surface alteration. Repeated indications of surface softening, however, averaging 6 points R_c and locally as great as 8 points R_c, were measured on this surface. The abusive condition shows evidence of a thin altered layer, presumably plastically deformed and overtempered. Hardness changes were similar to those found for the gentle milling condition. Untempered martensite, however, as would be evidenced by a light etching layer is not visible. Indicated hardness data are R_c values converted from Knoop microhardness measurements. Surface finish measurements are averages of readings made on all specimens from each group.

Magnifications: 1000X

ORIENTATION: TRANSVERSE MILL. SURFACE SECTIONS PERPENDICULAR TO LAY.

Figure 27
SURFACE CHARACTERISTICS OF 4340 MODIFIED (QUENCHED AND TEMPERED, 53 R_c, 285 KSI) PRODUCED BY END MILLING - END CUTTING

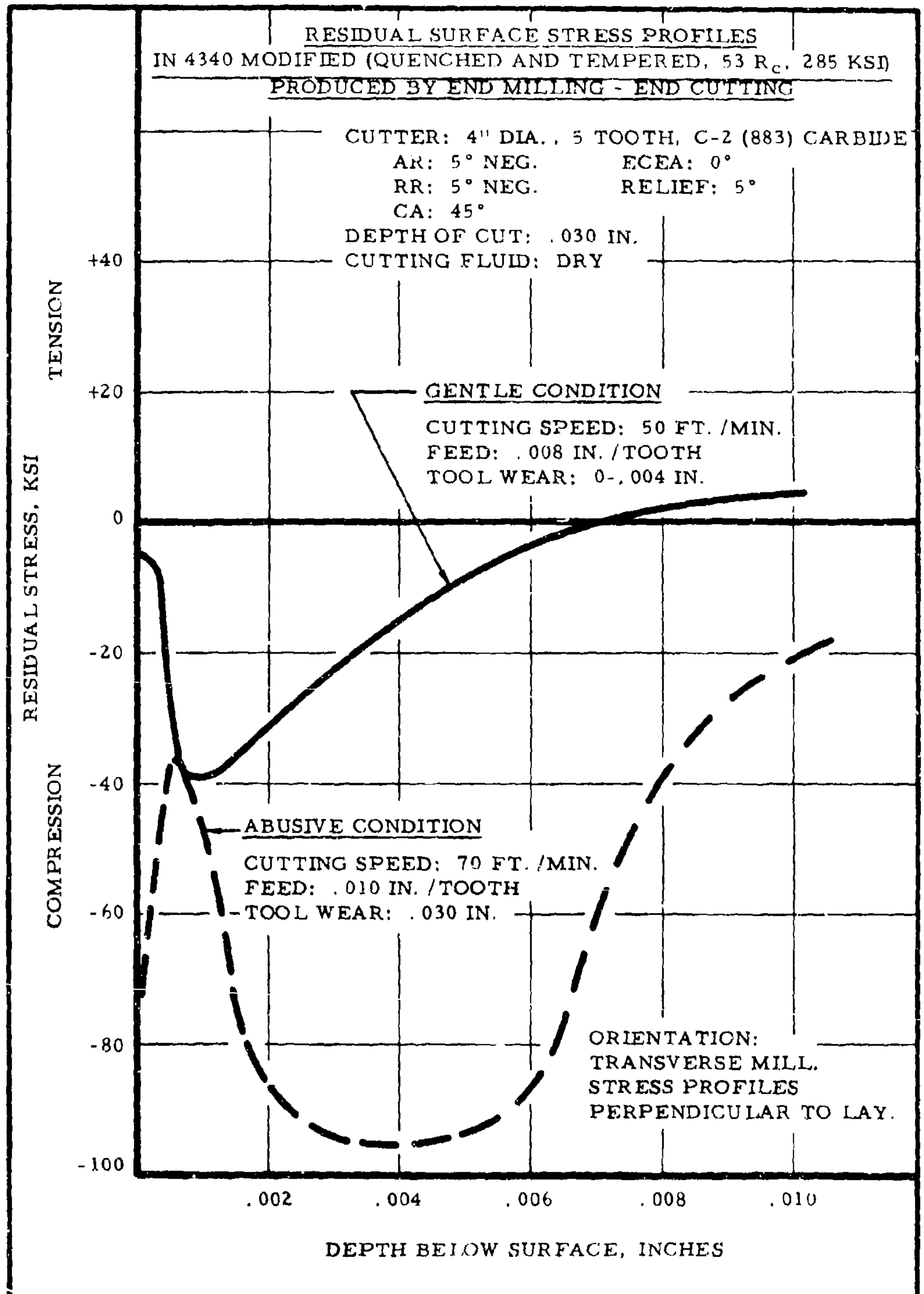


Figure 28
RESIDUAL STRESS IN 4340 MODIFIED: END MILLING - END CUTTING

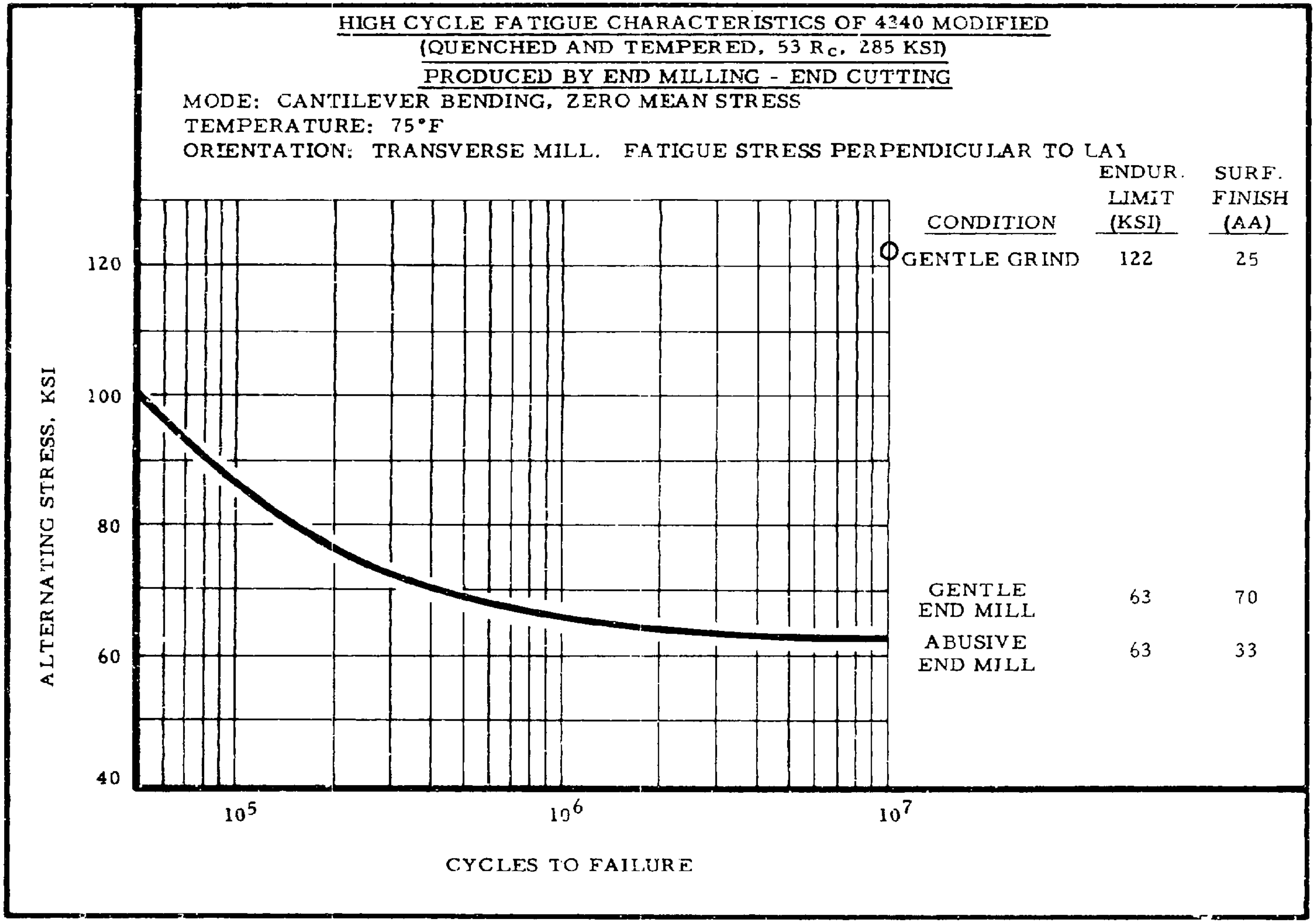


Figure 29
HIGH CYCLE FATIGUE OF 4340 MODIFIED: END MILLING - END CUTTING

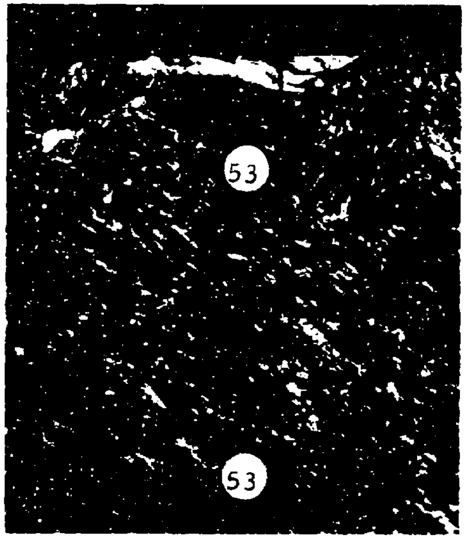
6.2.4 Drilling - AISI 4340 Modified, Q & T, 53 R_c, 285 ksi

Metallography

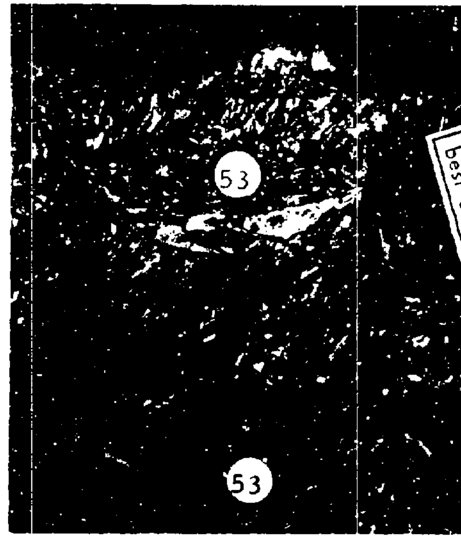
Drilling tests were run under a variety of conditions on coupons of 4340 Modified to explore the range of metallographic effects associated with drilling variables. Tests were run with sharp drills, medium sharp drills, and dull drills, both with and without a cutting fluid. Drilling conditions are summarized in Table VII. The technique used is described in Appendix I-7.

Photomicrographs of cross sections of drilled holes at 1000X are shown in Figure 30. The sections chosen for photomicrographs are all taken from walls of the hole, midway through the test coupon. Figure 30 (a) is typical of that produced by a sharp drill having essentially no wearland at the start of the cut. No surface alterations are in evidence, although a small quantity of built up edge which is highly deformed (light etching) has been smeared into the surface in the center of the photomicrograph. No microhardness increase or decrease was associated with the hole produced by the sharp drill. Figure 30 (b) shows the surface produced by a somewhat duller drill having an initial wearland of .008". Here again, no surface layer alterations or changes in microhardness were observed. The bore of the hole is noticeably rougher than that produced between dead sharp drills. The result of using a dull drill is shown in Figure 30 (c). In evidence are multiple tears or cracks and laps typically associated with the built up edge which forms when drilling high strength steel with dull drills. A close look at this photomicrograph also indicates the presence of a high degree of plastic deformation in the surface. Furthermore, rehardening has occurred as a result of localized heating in the vicinity of 60 R_c. This is approximately 7 points R_c higher than the hardness of the base metal. The total depth of the hardened zone was found to be as great as .004" as a result of drilling with a .030" wearland. All of the photomicrographs illustrate sections of holes which were produced with a cutting fluid (Cutmax) and with the levels of drill wear indicated.

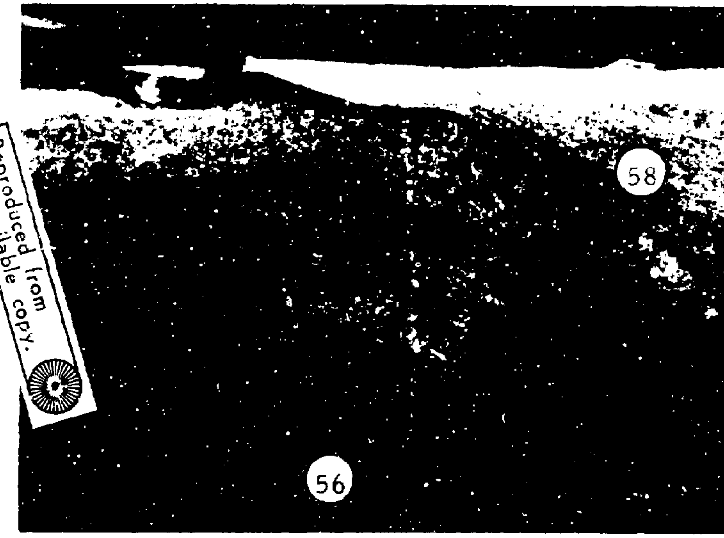
Due to the geometry of these test surfaces, residual stress and fatigue data were not obtained.



(a) Initial Drill Wearland: .000"



(b) Initial Drill Wearland: .008"



(c) Initial Drill Wearland: .030"

Photomicrographs showing cross sections of longitudinal surfaces of holes produced with drills having the various initial wearlands indicated above. Cutmax was used as a lubricant for all holes. Drilling was accomplished at 15 surface feet/minute and a feed of .0005 in./rev. using T15 drills, 1/4" diameter. Notice the relative freedom from surface alterations resulting from the use of sharp and moderately worn drills, Figures (a) and (b). Notice in contrast, the extensive plastic deformation, cracking, and surface rehardening associated with the use of a dull drill as shown in Figure (c). Indicated hardness data are R_c values converted from Knoop microhardness measurements.

Magnification: 1000X

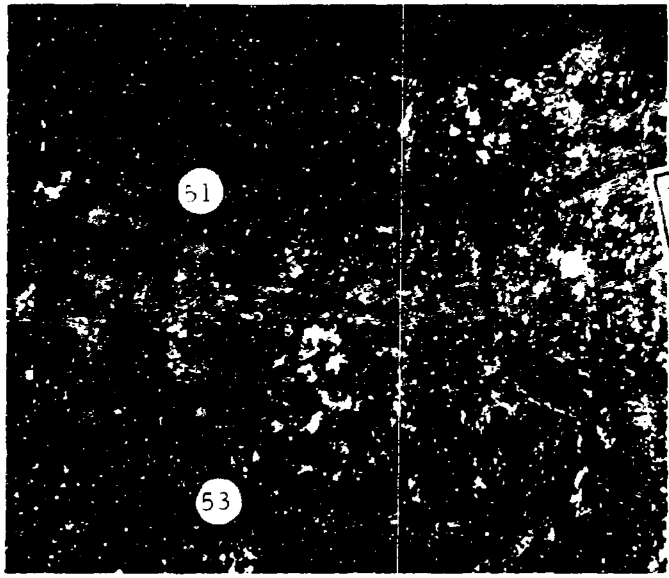
ORIENTATION: SURFACE SECTIONS ARE PARALLEL TO THE AXIS OF THE HOLE.

Figure 30
SURFACE CHARACTERISTICS OF 4340 MODIFIED (QUENCHED AND TEMPERED, 53 R_c, 285 KSI) PRODUCED BY DRILLING

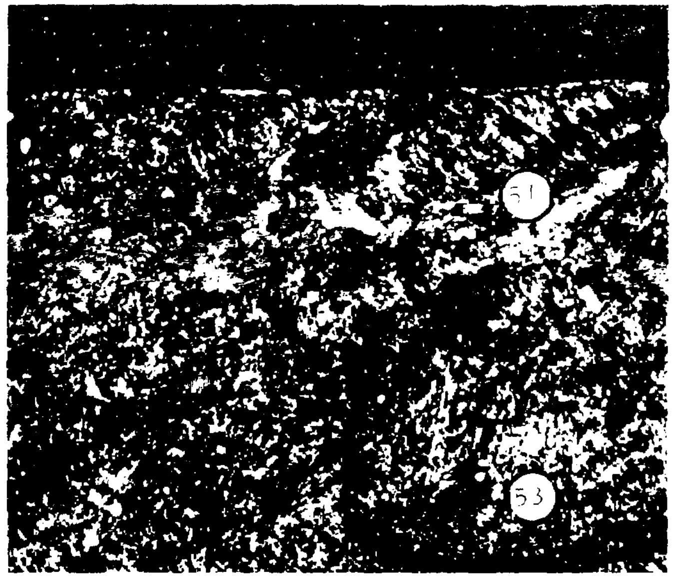
6.2.5 ECM - AISI 4340 Modified, Q & T, 53 R_c, 285 ksi

Photomicrographs of the surface structures of 4340 Modified produced by ECM are shown in Figure 31. Both photomicrographs in this illustration show the sample to be free of heat effected zones or plastically deformed layers. This is typical of ECM. Microhardness examination showed a slight loss in hardness at the surface of both samples, approximating two points R_c. This slight degree of surface softening has also been reported on several occasions associated with ECM processing.

The electrolyte used on the samples illustrated in Figure 31 was NaCl. Samples were also ECM'd using $NaNO_3$ as an electrolyte with essentially the same result.



(a) Standard Conditions
Surface Finish: 80 AA



(b) Off-Standard Conditions
Surface Finish: 200+ AA

The above photomicrographs are typical of an ECM surface. Absence from thermal disturbance and plastic deformation at the surface is easily verified. Indicated hardness data are R_c values converted from Knoop microhardness measurements. Surface finish measurements are averages of readings made on all specimens from each group.

Magnification: 1000X

Figure 31
SURFACE CHARACTERISTICS OF 4340 MODIFIED (QUENCHED AND TEMPERED, 53 R_c, 285 KSI) PRODUCED BY ECM

6.3 18% Nickel Grade 300 Maraging Steel, Solution Treated and Aged, 54 R_C

A summary of the high cycle fatigue behavior of this grade of maraging steel is shown in Figure 32. In general, this limited data shows virtually no sensitivity to variations in either hand sanding or end milling. Conventional and abusive surface grinding exhibited a moderate fatigue depression when compared to the effects of low stress grinding. This depression, however, is considerably smaller than that exhibited by the martensitic steels as well as the titanium and nickel alloys when comparing the effects of abusive versus gentle grinding.

The same type of behavior has been previously observed for the 18% nickel maraging steels when preliminary studies in component distortion were made as a result of grinding and milling both the 250 and 300 grades under several conditions. In these previous efforts, the maraging steels were much less prone to distortion as a result of abusive machining than any of the other alloys studied.

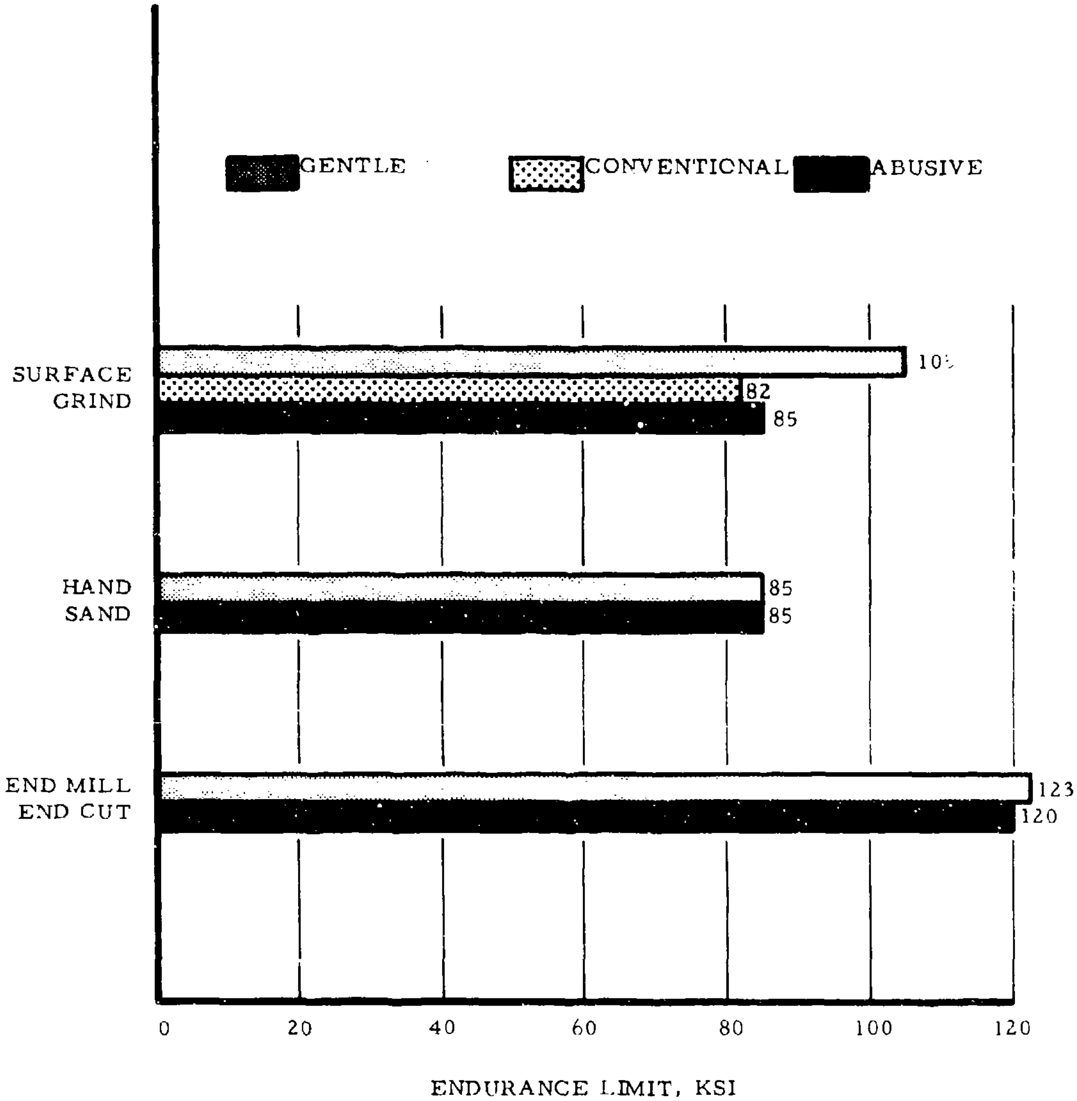


Figure 32
SUMMARY OF HIGH CYCLE FATIGUE BEHAVIOR
OF 18% NICKEL GRADE 300 MARAGING STEEL
(SOLUTION TREATED AND AGED, 54 R_c)

6.3.1 Surface Grinding - 18% Ni Grade 300 Maraging Steel, STA, 54 R_c

Metallography

Photomicrographs of surface structures produced in Grade 300 maraging steel evaluated under gentle, conventional, and abusive conditions are shown in Figure 33. The grinding conditions used for making the test cuts on these specimens are summarized in Table II.

Gentle grinding shows no microstructural evidence of subsurface alteration, either from plastic deformation or surface overheating which occurred. Small random light etching patches may be seen on the surface, although they have not been identified. A surface softening of .0005 to .001 in. deep was measured on the gently ground samples. The extent of the softening was about 3 points R_c.

The conventionally ground samples which were studied metallographically showed no structural evidence of deformation or subsurface overheating. Additional disturbed patches which were very light etching were found on the surface. The conventional grinding, however, caused a greater surface hardness loss. This loss was as great as 6 points R_c and extended for a depth of .001 to .002 inches.

Abusive surface grinding produced marked structural evidence of surface overheating as indicated in Figure 33 (c). A light etching layer, probably of resolutioned material, approximately .002 in. deep, is very evident. A thin continuous completely white etching layer may also be seen on the surface of abusively ground samples. Neither the identity of this extreme outer layer nor its hardness was established. Hardness loss due to abusive grinding of approximately 10 points R_c was observed. Several hardness readings were taken within the first .001 in. of the surface, which ranged from 41 to 45 R_c.

Residual Stress

Residual stress profiles observed on maraging steel using the grinding conditions chosen for this program are shown in Figure 34. An unusual similarity is displayed among the patterns of all three of the grinding conditions studied. All exhibited a peak subsurface compression of 40 ksi, followed by a relatively low stress tension field not exceeding 25 ksi. As

6.3.1 Surface Grinding - 18% Ni Grade 300 Maraging Steel, STA, 54 R_c (continued)

Residual Stress (continued)

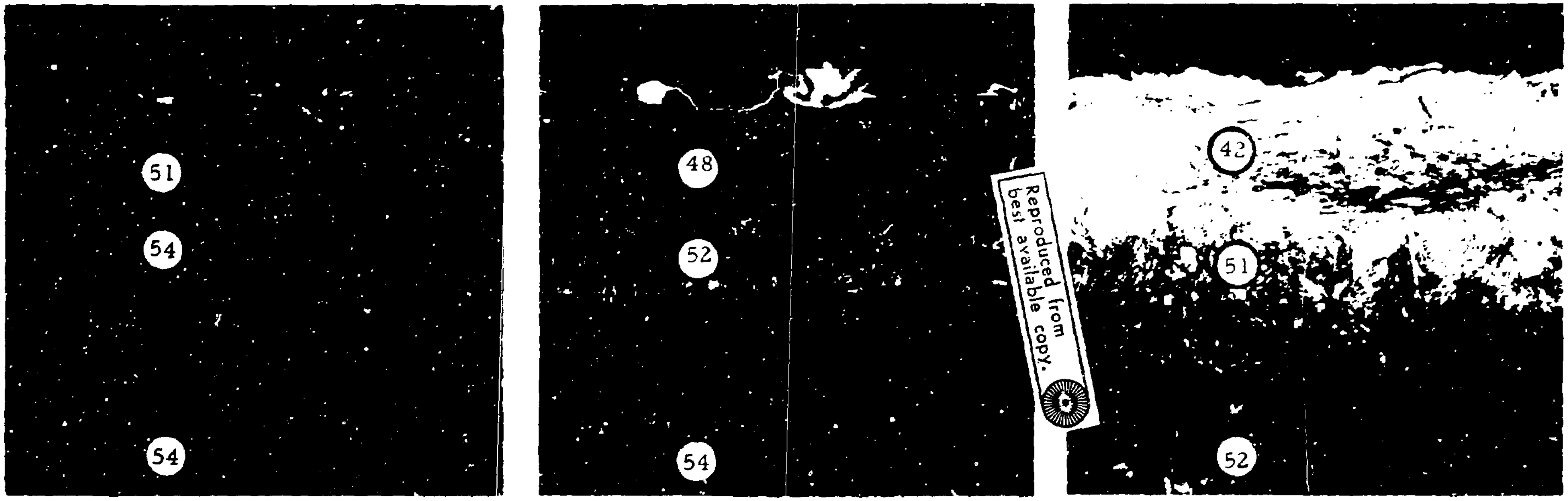
the grinding becomes more severe, the tension zone becomes deeper and the peak tension stress higher. Compared to stress levels produced in other materials, however, the stresses measured in maraging steel are very low. The reason for the occurrence of very low residual stresses in maraging steel is not completely understood at the present time. It is very evident, however, that the low, balanced surface stress reaction is responsible for the minimum amounts of distortion which are evidenced by this material as a result of a grinding operation. Consequently, this maraging steel is relatively easy to control dimensionally during processing by grinding.

High Cycle Fatigue Strength

Fatigue strengths observed in maraging steel finished by different grinding procedures are summarized in Figure 35. A listing of actual test data is presented in Table XV. Gentle surface grinding produces a fatigue strength (measured at the 10^7 endurance level) of 105 ksi. Conventional and abusive grinding depress the fatigue strength to 82 and 85 ksi, respectively. The loss in fatigue strength due to conventional grinding is probably the result of austenite reversion due to localized surface overheating. This is indicated by a loss of hardness and in more extreme instances by changes in microstructure. In terms of fatigue response, however, the 18% Ni maraging steels exhibit considerably less sensitivity to grinding damage than the other high strength steels evaluated. A related behavior has also been exhibited (in other efforts) by the minimal distortion tendencies of these alloys.

Stress Corrosion

A few stress corrosion tests were run on surface ground samples of this alloy per the procedure described in Appendix II-5. Specimen life ranged from failure in 200 hours to removal without failure after 1000 hours. The data, however, were inconclusive with respect to the relative stress corrosion sensitivity of these surfaces. Individual data points are summarized in Table XXVIII.



(a) Gentle Grinding
Surface Finish:
Perpendicular to lay: 28 AA
Parallel to lay: 16 AA

(b) Conventional Grinding
Surface Finish:
Perpendicular to lay: 31 AA
Parallel to lay: 24 AA

(c) Abusive Grinding
Surface Finish:
Perpendicular to lay: 51 AA
Parallel to lay: 36 AA

Gentle and conventional grinding show no evidence of microstructural changes due to either plastic deformation or overheating. Isolated patches of an unidentified white constituent may be seen on both surfaces. A greater quantity of this material is present in the conventionally ground sample; compare (b) to (a). Abusive grinding produced an extensive thermal disturbance, visibly .002 in. deep and consisting of resolutioned material. Note also the continuous white etching surface layer, approximately .0001 in. thick. All samples exhibited surface softening to the extent indicated on the photomicrographs. The greatest effect was in the abusive ground sample where surface softening, approximately .004 in. deep in total, was measured. Hardness measurements are R_c values converted from Knoop readings. Surface finish measurements are the averages of readings made on all specimens from each group.

Magnifications: 1000X

ORIENTATION: LONGITUDINAL GRIND. SURFACE SECTIONS PERPENDICULAR TO GRINDING LAY.

Figure 33
SURFACE CHARACTERISTICS OF 18% NICKEL GRADE 300 MARAGING STEEL
(SOLUTION TREATED AND AGED, 54 R_c)
PRODUCED BY SURFACE GRINDING

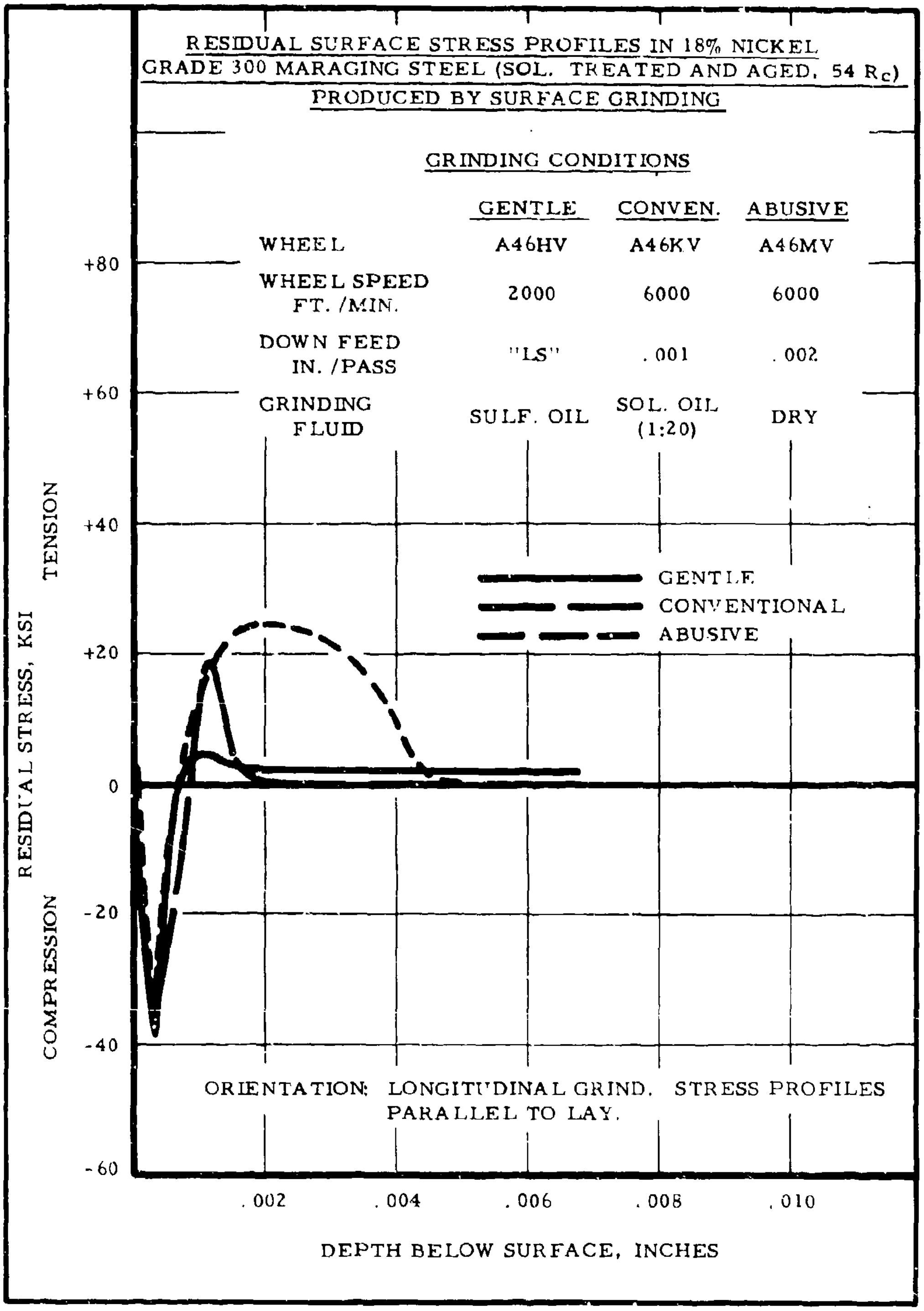


Figure 34
RESIDUAL STRESS IN 18% NICKEL GRADE 300 MARAGING: SURFACE GRINDING

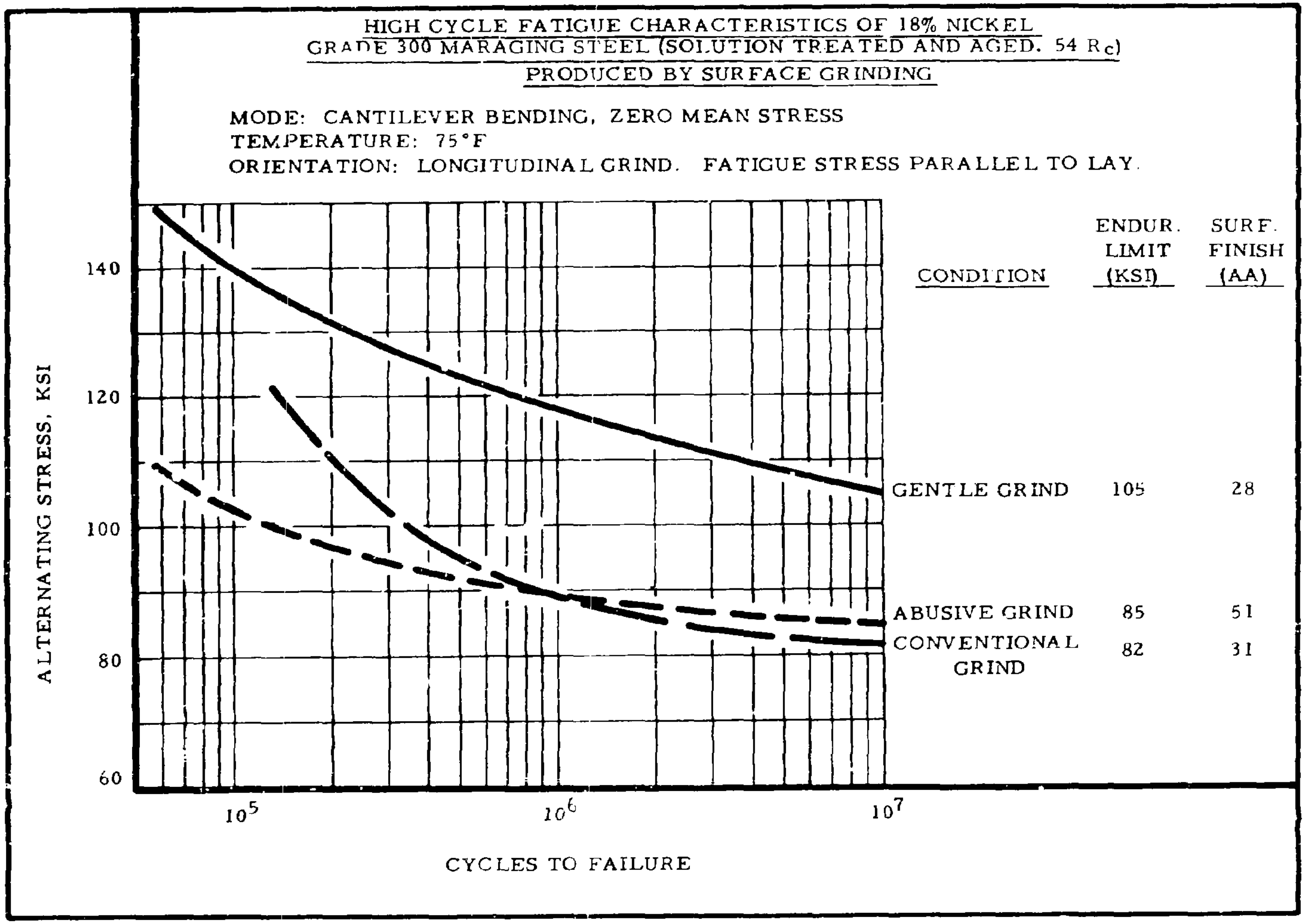


Figure 35
HIGH CYCLE FATIGUE OF 18% NICKEL GRADE 300 MARAGING: SURFACE GRINDING

6.3.2 Hand Sanding - 18% Ni Grade 300 Maraging Steel, STA, 54 R_c

Metallography

Photomicrographs showing cross sections of maraging steel finished by hand disc sanding are shown in Figure 36. An extremely thin layer which may be a surface alteration is visible on each surface. No variations in microhardness were measured, however, at distances as close at .001" from the surface. Visually, it may be concluded that even the abusive sanding operation is producing no detectable surface damage. This is typical of behavior exhibited by this process in other materials as well.

Residual Stress

An indication of the residual stress profiles produced in maraging steel by gentle and abusive hand sanding are shown in Figure 37. Shallow compressive stresses were produced by both conditions. This stress profile behavior is similar to that observed for 4340 Modified, judged to be typical of martensitic steels. As may be seen by comparing Figure 37 with the residual stress profiles obtained on 4340 Modified due to hand sanding, Figure 25, behavior is very similar. In neither case does it appear that sufficient localized heat is generated by sanding to cause phase transformations or other effects which would be adverse to requirements for good surface integrity.

High Cycle Fatigue Strength

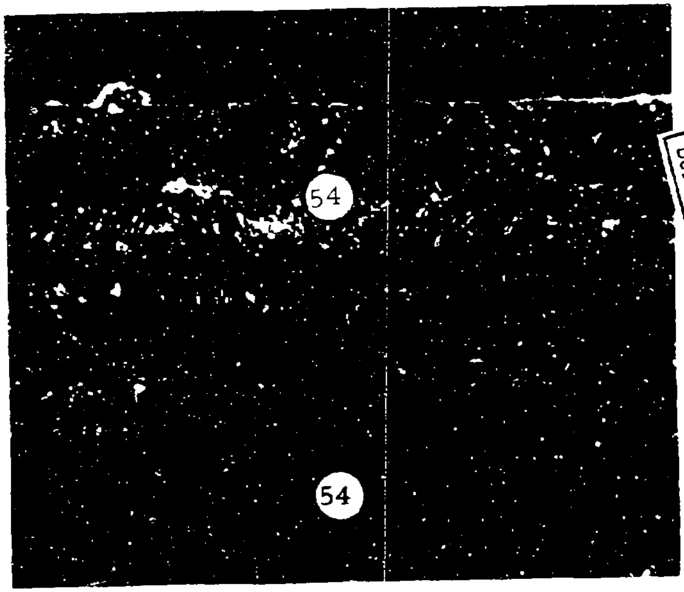
The high cycle fatigue behavior of hand sanded maraging steel of this type is shown in Figure 38. The data resulting from all of the test specimens which had been disc sanded under gentle conditions and those sanded under abusive conditions fell closely on a single curve defining the S/N behavior of the alloy. An approximate endurance limit or fatigue strength at the 10^7 runout level was indicated as 85 ksi. Individual test points are presented in Table XV.

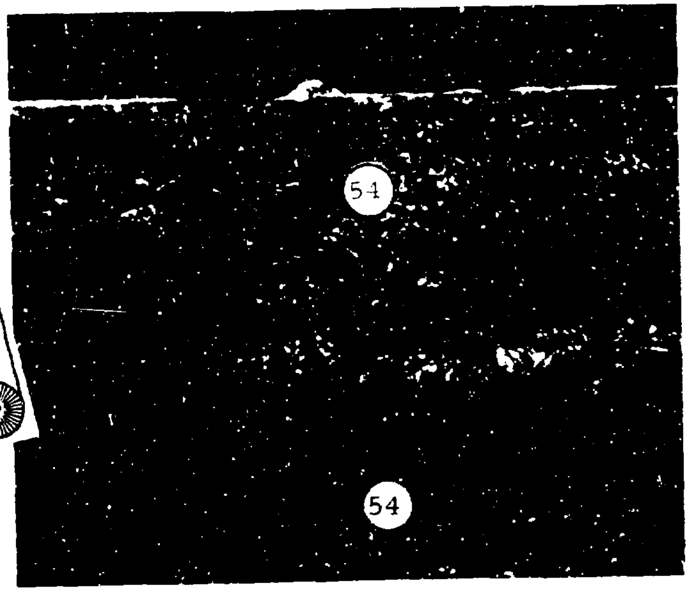
Considering the similar photomicrographs and residual stress profiles, it is not surprising that the fatigue strength behavior of this alloy should be unaffected by hand sanding under gentle versus abusive conditions. The same general behavior was also observed for 4340 Modified as shown in Figure 26.

6.3.2 Hand Sanding - 18% Ni Grade 300 Maraging Steel, STA, 54 R_c (continued)

Stress Corrosion

Limited stress corrosion data were obtained on hand sanded maraging steel samples. Specimen lives ranged from approximately 200 to 850 hours, but in such a distribution as to be inconclusive regarding possible effects of surface condition on stress corrosion susceptibility. The data obtained are summarized in Table XXVIII.





(a) Gentle Sanding
Surface Finish:
Perpendicular to lay: 10 AA
Parallel to lay: 10 AA

(b) Abusive Sanding
Surface Finish:
Perpendicular to lay: 15 AA
Parallel to lay: 15 AA

Traces of a thin continuous white layer may be found on both gently and abusively produced surfaces. The photomicrographs, however, indicate that any surface alteration is extremely shallow. This observation is verified by the uniform microhardness of the alloy, measured to be 54 R_C. Indicated hardness data are R_C values converted from Knoop microhardness measurements. Surface finish measurements are averages of readings made on all specimens from each group.

Magnification: 1000X

ORIENTATION: TRANSVERSE SAND. SURFACE SECTION PERPENDICULAR TO SANDING LAY.

Figure 36
SURFACE CHARACTERISTICS OF 18% NICKEL, GRADE 300 MARAGING STEEL
(SOLUTION TREATED AND AGED, 54 R_c)
PRODUCED BY HAND SANDING

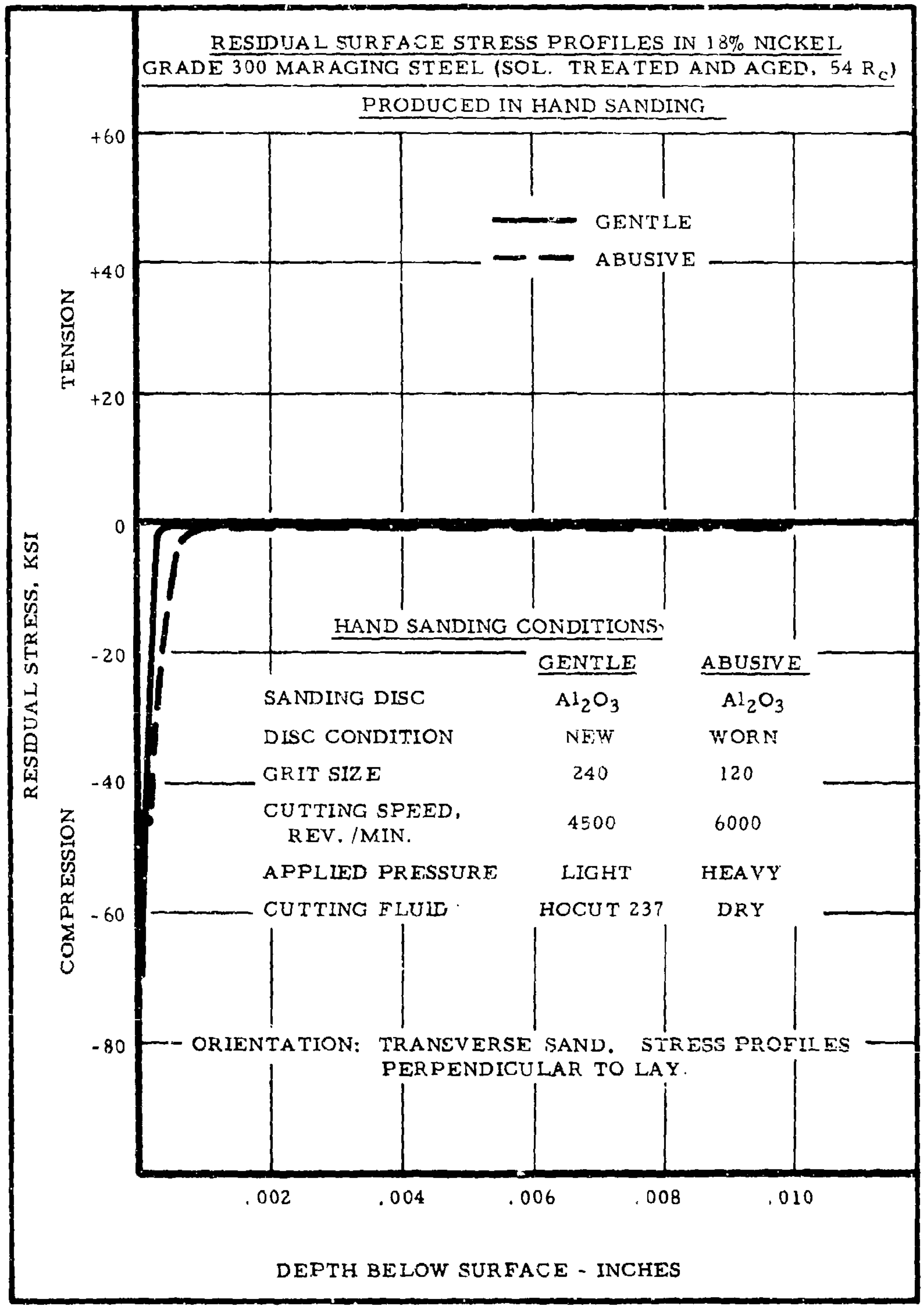


Figure 37
RESIDUAL STRESS IN 18% NICKEL, GRADE 300 MARAGING: HAND SANDING

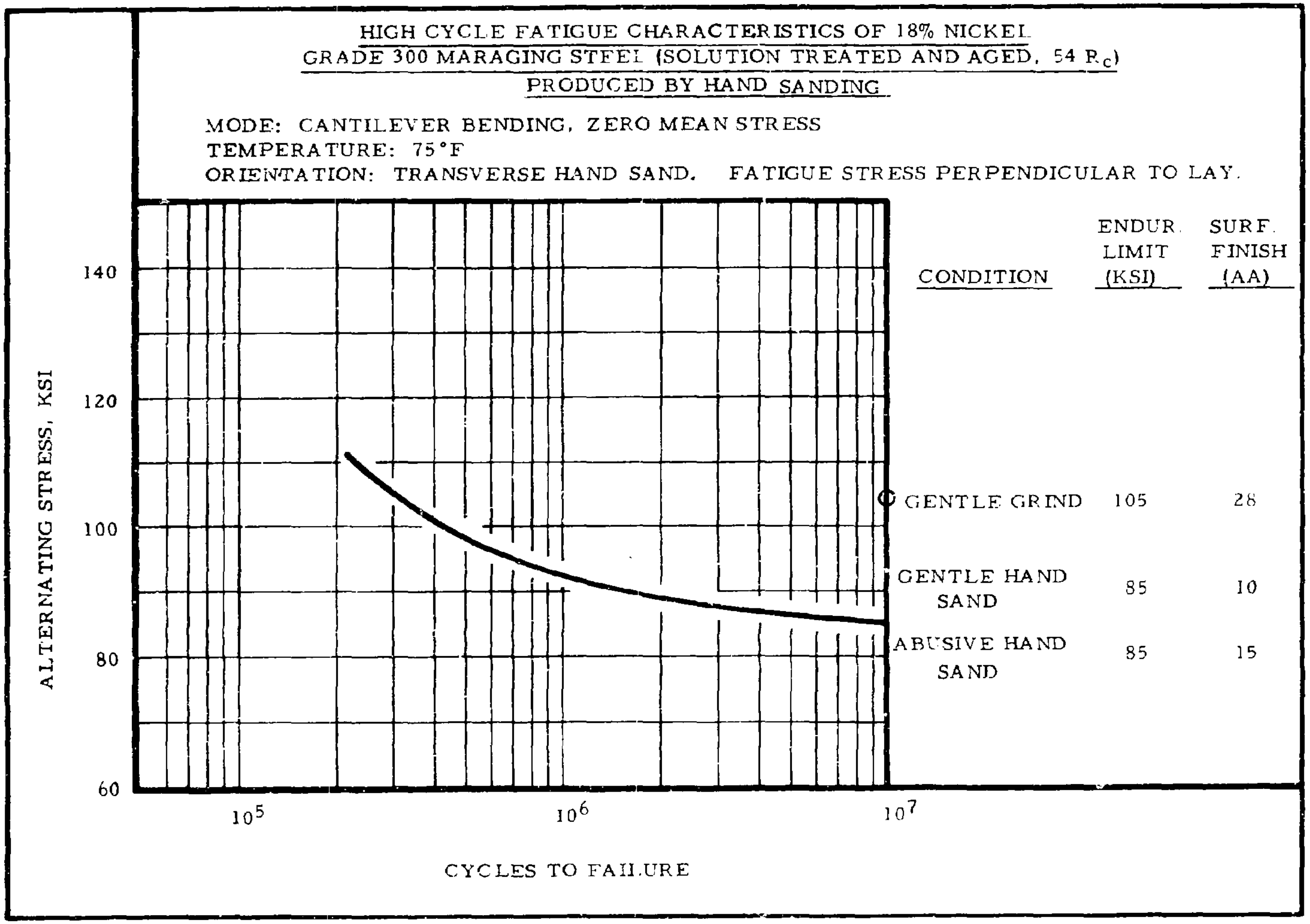


Figure 38
HIGH CYCLE FATIGUE OF 18% NICKEL GRADE 300 MARAGING: HAND SANDING

6.3.3 End Milling-End Cutting - 18% Ni Grade 300 Maraging Steel, STA, 54 R_c

Metallography

Photomicrographs of structures produced by gentle and abusive end milling-end cutting of maraging steel are shown in Figure 39. Milling conditions used for making test cuts on this alloy are summarized in Table IV. Both structures show evidence of a relatively continuous white etching layer which was also observed in trace and greater quantities on ground surfaces. No significant subsurface evidence of overheating or plastic deformation is evident in the microstructures. However, both samples showed evidence of surface softening to the extent of about 3 to 4 points R_c as indicated on the photomicrographs in Figure 39.

Residual Stress

Residual stress profiles produced in maraging steel using the end cutting conditions indicated are shown in Figure 40. Notice that both milling conditions produced moderate compressive stresses in the range of 70 to 80 ksi and that the patterns are generally similar. Abusive milling does, however, exert an effect for a greater depth beneath the surface. These stresses are somewhat higher in compression than those produced by gentle grinding, 40 ksi. As indicated in Figure 40, the total affected depth from abusive versus gentle milling is approximately .007 versus .003 inches.

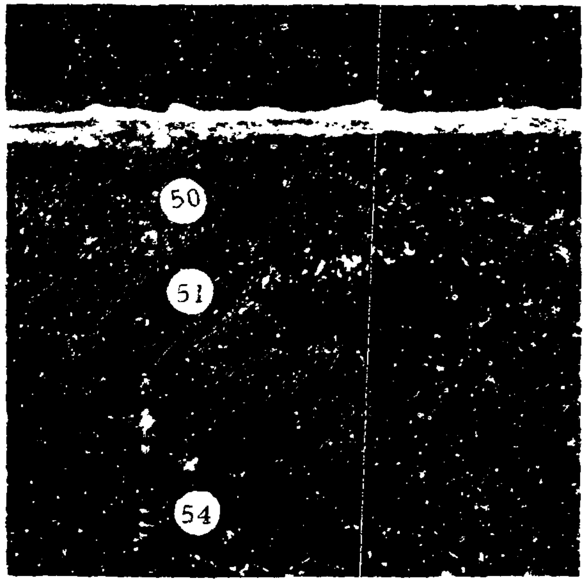
High Cycle Fatigue Strength

The fatigue strengths measured in maraging steel samples resulting from the milling study are shown in Figure 41. Endurance limits are essentially the same for both conditions, namely, 123 and 120 ksi for gentle and abusive milling, respectively. The closeness of these two endurance limits is not surprising when one considers the similarity in microstructure, microhardness, and residual stress profile of each surface. It is also worthy to note that the fatigue strength levels are somewhat higher than those obtained from the ground samples. This behavior would indicate a possible relationship between surface residual stress and fatigue strength in this material since the higher fatigue strengths are matched with the higher peak compressive stress levels. Fatigue data are summarized in Table XV.

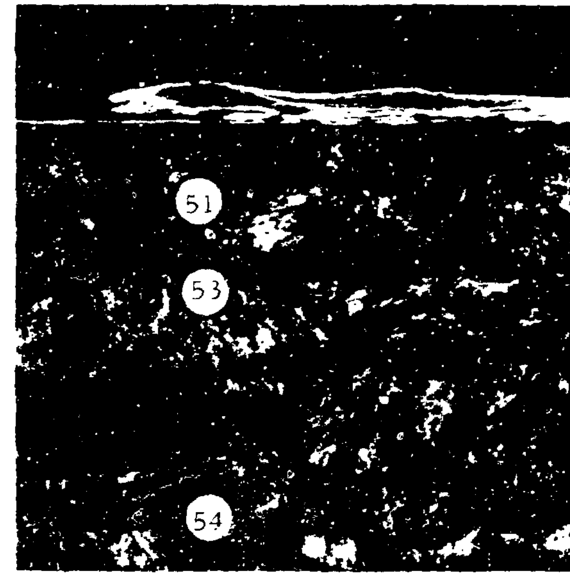
6.3.3 End Milling-End Cutting - 18% Ni Grade 300 Maraging Steel, STA, 54 R_c (continued)

Stress Corrosion

A few stress corrosion tests were run on milled maraging steel samples using the alternate immersion in salt water procedure described in Appendix II-5. In this particular instance, all of the gently milled samples were removed after a 1000 hour exposure without failure. Abusively milled samples had lives ranging from approximately 500 hours to removal without failure at 1000 hours. Considering the total stress corrosion behavior of maraging steel, however, it appears unwise to draw any specific conclusions from this limited data. Actual data points are contained in Table XXVIII.



(a) Gentle Milling
Surface Finish:
Perpendicular to lay: 32 AA
Parallel to lay: 10 AA



(b) Abusive Milling
Surface Finish:
Perpendicular to lay: 18 AA
Parallel to lay: 9 AA

A continuous white etching layer may be seen on both surfaces. Gentle milling shows possible evidence of a thin distorted layer immediately under the white etching layer, although the total depth of this visible distortion does not exceed .0001 in. The abusively milled surface shows evidence of a highly distorted built up edge. This condition was observed consistently in all three of the samples of each milling condition which were checked in this way. Rockwell hardness data (converted from Knoop measurements) indicate a 3 to 4 point R_c loss in the first .001 in. of the surface of each sample. Surface finish measurements are averages of readings made on all specimens from each group.

Magnification: 1000X

ORIENTATION: TRANSVERSE MILL. SURFACE SECTIONS PERPENDICULAR TO LAY.

Figure 39
SURFACE CHARACTERISTICS OF 18% NICKEL GRADE 300 MARAGING STEEL
(SOLUTION TREATED AND AGED, 54 R_c)
PRODUCED BY END MILLING - END CUTTING

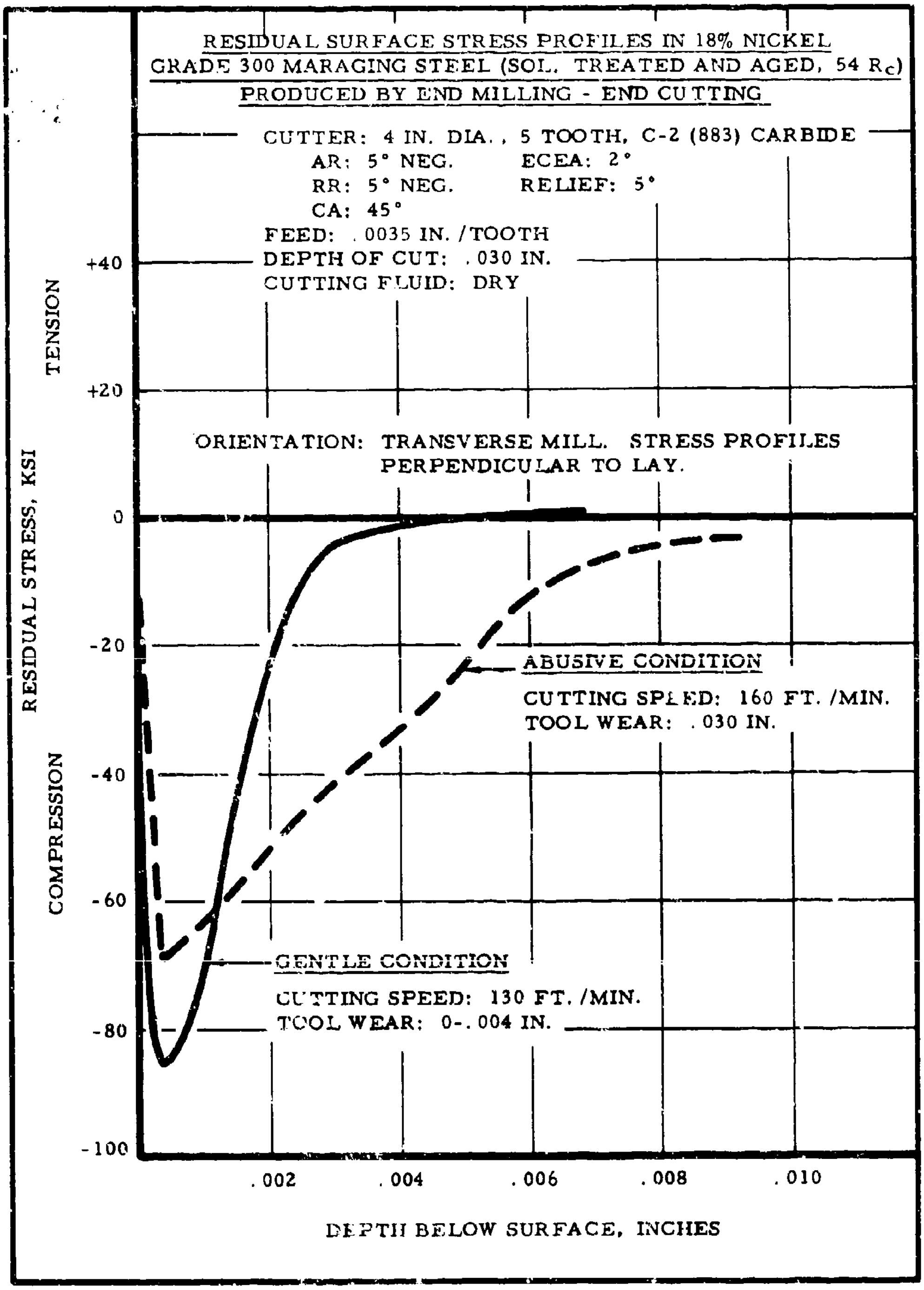


Figure 40
RESIDUAL STRESS IN 18% NICKEL GRADE 300 MARAGING:
END MILLING - END CUTTING

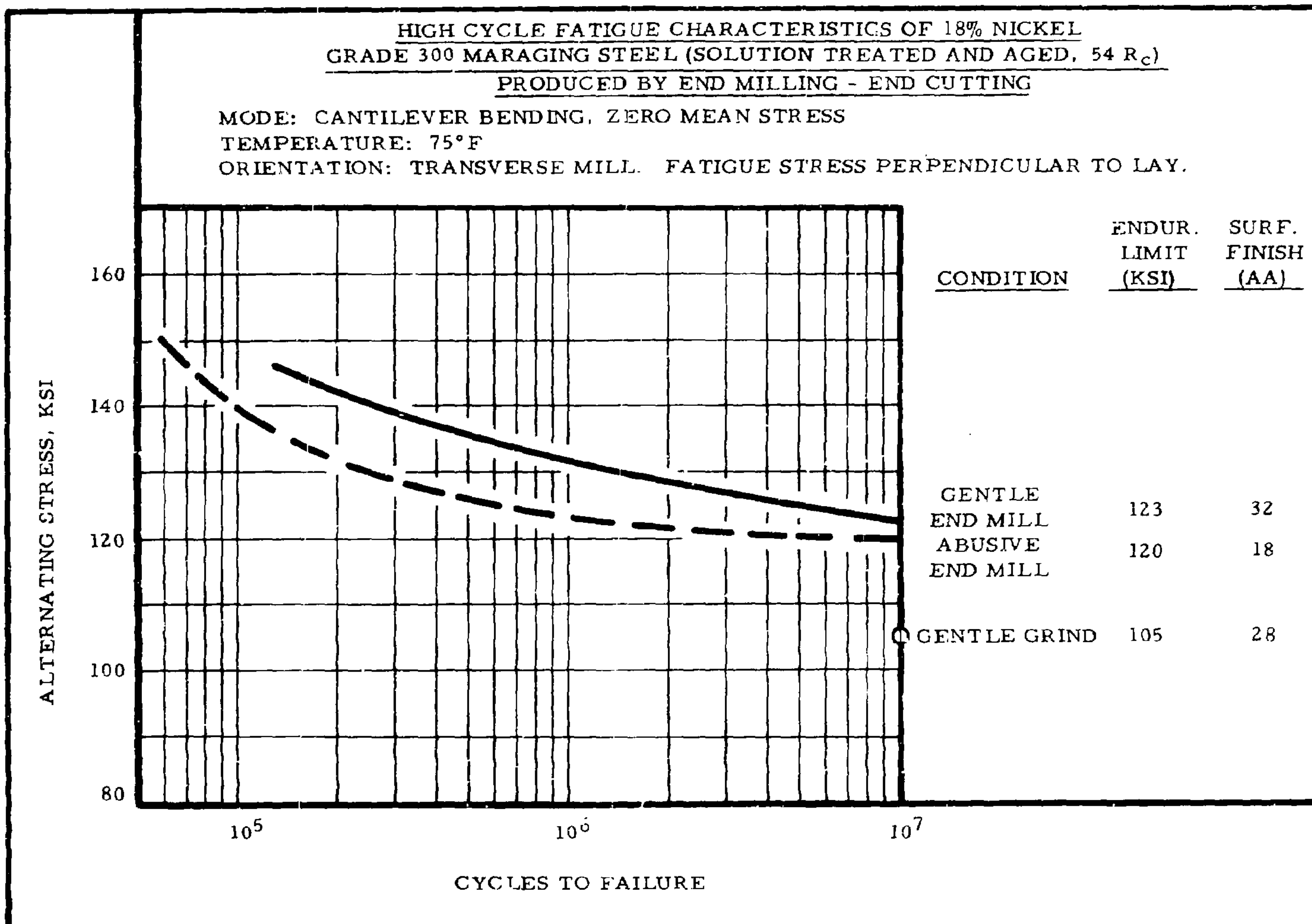


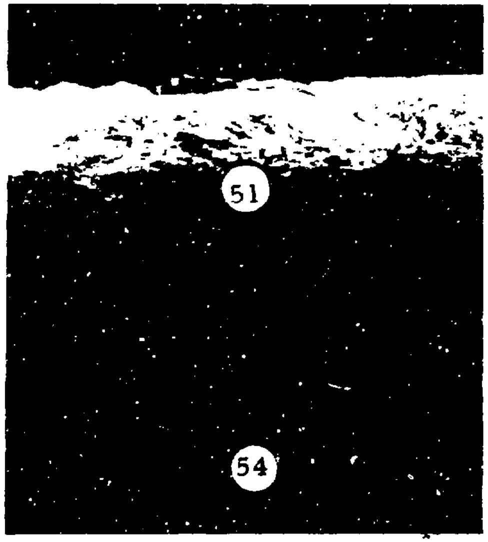
Figure 41
HIGH CYCLE FATIGUE OF 18% NICKEL GRADE 300 MARAGING:
END MILLING - END CUTTING

6.3.4 Drilling - 18% Ni Grade 300 Maraging Steel, STA, 54 R_c

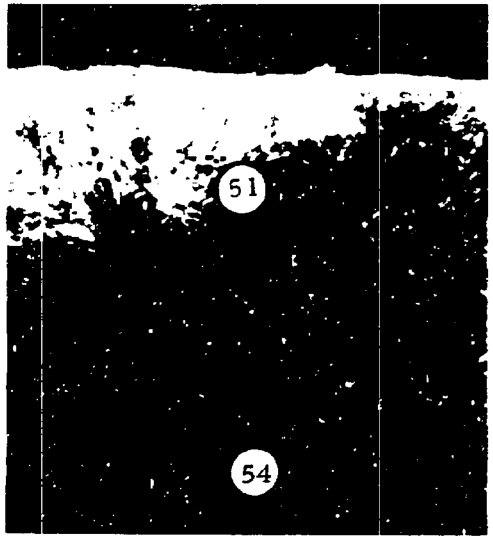
Metallography

Drilling tests were performed on this grade of maraging steel primarily to determine metallographic response of drilled surfaces to a wide variety of drilling conditions. Various conditions evaluated are as summarized in Table VII. The testing procedure used was as described in Appendix I-7.

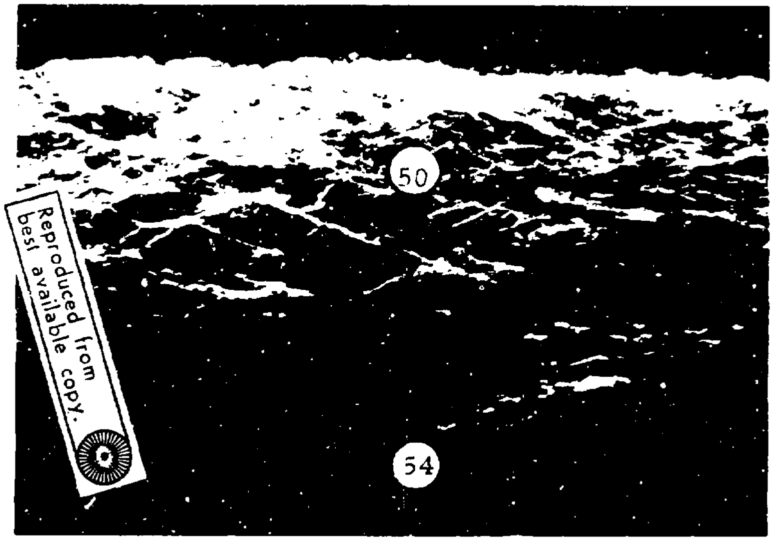
As can be seen from Figure 42, all of the drilling conditions evaluated produced rather large surface alterations in the material. The sharpest drill used produced a thinner distorted layer, one as seen in Figure 42 (a), but one which is highly worked and one which contained a number of tears or laps. The dullest drill produced a rather deep layer of transformation which is evidenced by the pronounced twinning pattern shown in Figure 42 (c). Microhardness data indicated a surface loss of approximately 4 points R_c at a depth of .001" beneath the surface for all three conditions. Residual stress and mechanical properties data were not obtained because of the geometry of the test surface. The surface integrity of these drilled holes, however, would have to be further evaluated in a specific application in order to qualify a particular condition for production.



(a) Initial Drill Wearland: .000"



(b) Initial Drill Wearland: .008"



(c) Initial Drill Wearland: .030"

Cross sections of surfaces of drilled holes resulting from various initial wearlands on the drill. All holes were produced using 1/4" diameter, type T15 drills, operated at 15 surface ft./min. and a feed of .0005 in./rev. Cutmax was used as the fluid in all cases. It will be noticed that significant surface distortion, largely occurring as plastic deformation with the presence of some laps and tears, was produced by all of the drilling conditions evaluated. All surfaces showed a microhardness loss of 3 to 4 points R_C. This is presumably due to a combination of localized heating and plastic deformation. Indicated hardness data are R_C values converted from Knoop microhardness measurements. Surface finish measurements are averages of readings made on all specimens from each group.

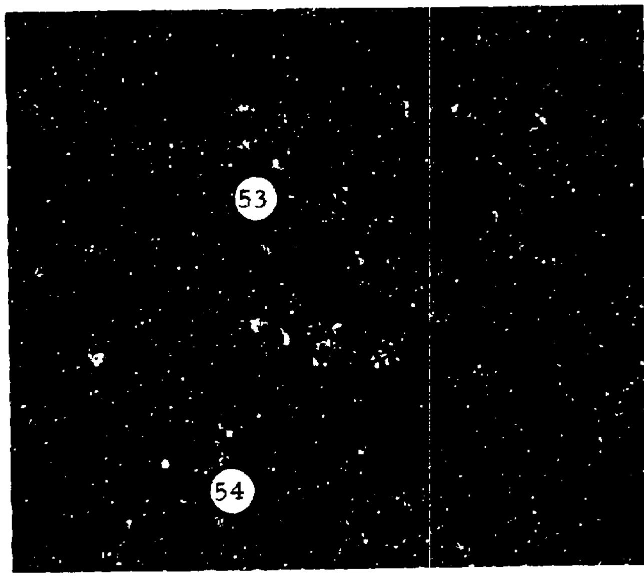
Magnification: 1000X

ORIENTATION: SURFACE SECTIONS ARE PARALLEL TO THE AXIS OF THE HOLE

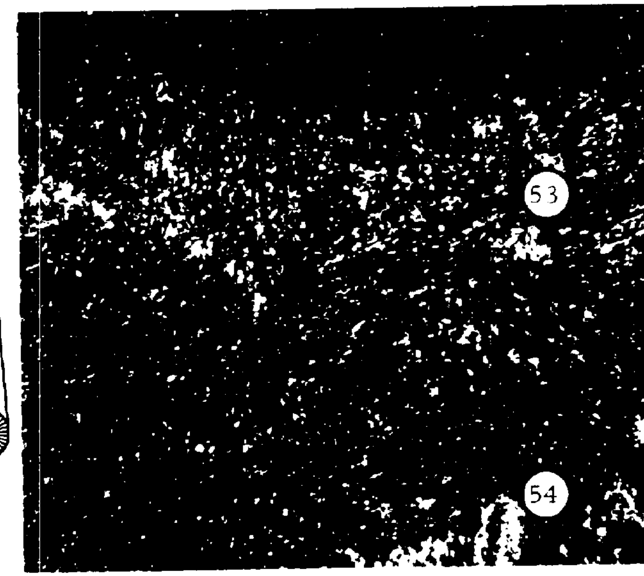
Figure 42
SURFACE CHARACTERISTICS OF 18% NICKEL GRADE 300 MARAGING STEEL
(SOLUTION TREATED AND AGED, 54 R_c)
PRODUCED BY DRILLING

6.3.5 ECM - 18% Ni Grade 300 Maraging Steel, STA, 54 R_c

Photomicrographs of surface structures observed in maraging steel finished by ECM are shown in Figure 43. These are typical surfaces produced by ECM in that they are free of surface layers exhibiting any degree of alteration. The surface produced by the off-standard condition was considerably rougher than that produced by finishing conditions, 200 and 19 AA, respectively. Both NaCl and $NaNO_3$ were used as electrolytes to ECM this material with essentially equal results. Photomicrographs shown in Figure 43 were the result of using $NaNO_3$.



(a) Standard Conditions
Surface Finish: 19 AA



(b) Off-Standard Conditions
Surface Finish: 200AA

Surfaces of maraging steel finished by ECM are shown in the above figures. Typical of this process, there is no evidence of localized heating or plastic deformation. The somewhat rougher surface associated with off-standard ECM is typical of the process. The slight microhardness loss at the surface is also typical of ECM. Indicated hardness data are R_c values converted from Knoop microhardness measurements. Surface finish measurements are averages of readings made on all specimens from each group.

Magnification: 1000X

Figure 43

SURFACE CHARACTERISTICS OF 18% NICKEL
GRADE 300 MARAGING STEEL (SOLUTION TREATED AND AGED, 54 R_c)
PRODUCED BY ECM

6.4 Titanium 6Al-4V, Beta Rolled, 32 R_c

The majority of the surface integrity work that has been done on this alloy was accomplished in the previous AFML surface integrity contract with Metcut (F33615-68-C-1003). The purpose of work on beta rolled Ti-6Al-4V in the current contract was to determine the extent to which previously observed surface integrity behavior would also be manifest in the low cycle fatigue region.

A summary of fatigue data available to date from both the previous contract noted above and the present contract is summarized in Figure 44. As can be seen in this figure, abusive versus gentle processing under all conditions tested, except end milling-end cutting, showed a significant depression in fatigue strength to be associated with the abusive condition. The greatest difference was in the case of surface grinding where the fatigue strength was depressed from 62 to 13 ksi by shifting from the gentle to the abusive condition. Only end milling-end cutting reversed this trend, wherein the fatigue strength due to abusive conditions was higher than that due to gentle conditions, 77 versus 64 ksi.

Reviewing low cycle fatigue behavior, also shown in Figure 44, considerably less effect due to variations in processing is evident. In comparing the stress to produce a 20,000 cycle life, the levels exhibited by gentle versus abusive grinding were 92 versus 71 ksi. Percentage wise, this is a much smaller gap that the 62 versus 13 ksi evidenced in the high cycle fatigue region for the same process. In the case of end milling, the abusively milled surface actually performed somewhat better than the gentle milled surface, exhibiting fatigue strengths at 20,000 cycles of 108 versus 98 ksi, respectively.

Considering the overall response of this alloy, it must be concluded that the high cycle fatigue behavior of Ti-6Al-4V in the beta rolled condition is quite sensitive to variables in metal removal parameters. On the other hand, this alloy is relatively insensitive to these variables in the low cycle fatigue region where plastic strain is encountered in the surface area during testing.

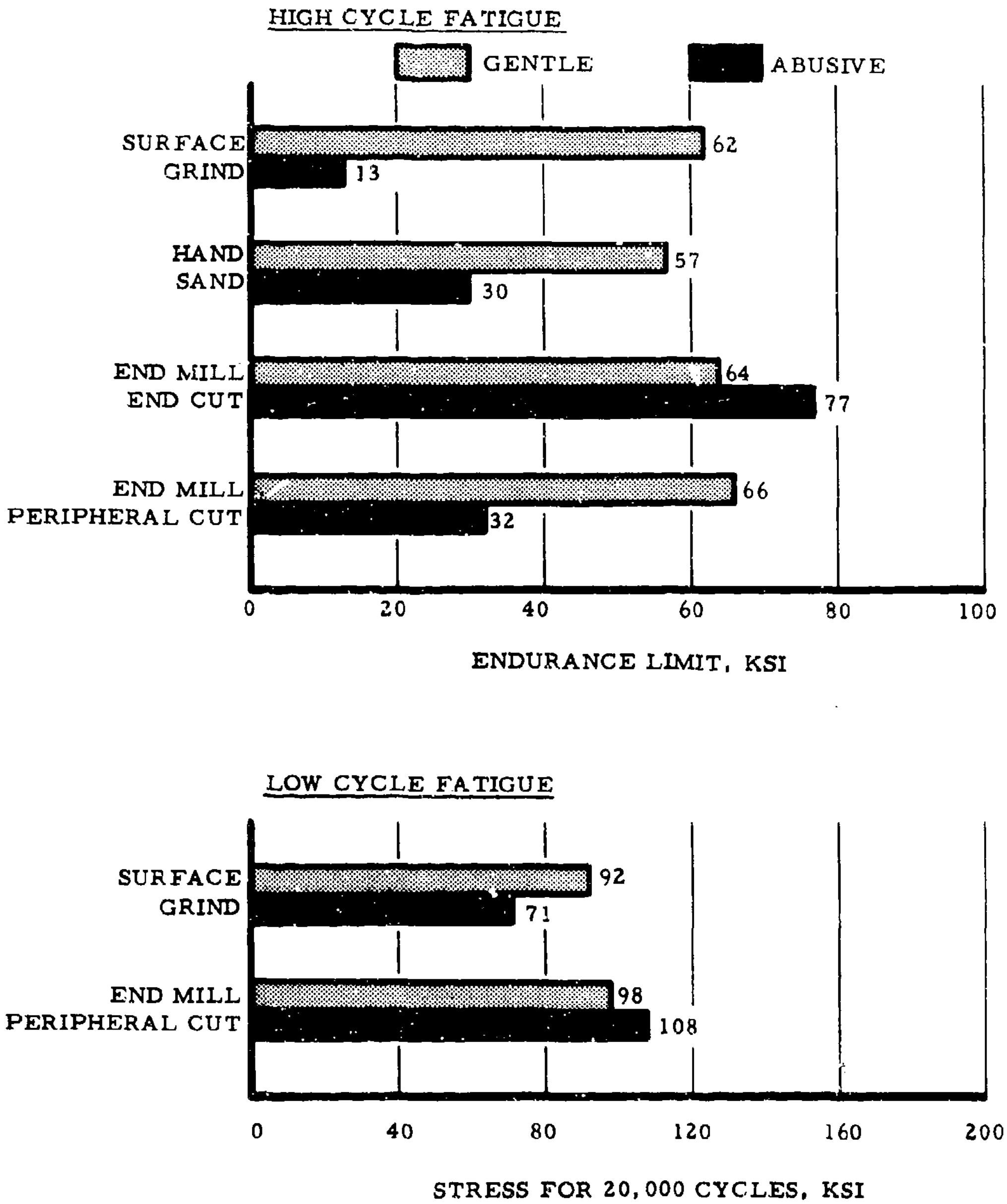


Figure 44
SUMMARY OF FATIGUE BEHAVIOR
OF TI-6Al-4V (BETA ROLLED, 32 R_c)

6.4.1 Surface Grinding - Ti-6Al-4V, Beta Rolled, 32 R_c

Metallography

Photomicrographs illustrating the effects of gentle, conventional, and abusive surface grinding on this alloy are shown in Figure 45. Typical of this process, gentle grinding produced no structural alterations nor any measurable degree of microhardness loss at the surface. Both conventional and abusive grinding conditions, also as shown in Figure 45, indicate a slight surface alteration in the form of a light etching layer and also a surface microhardness loss of approximately 4 points R_C. Presumably this hardness loss was due to localized heating during the grinding operation resulting in overaging of the structure in the surface area.

Residual Stress

Residual surface stress profiles for gentle and abusive grinding are shown in Figure 46. Gentle grinding is shown to produce relatively low surface stresses, but tensile in nature. The surface peak is approximately 30 ksi and there is a subsurface peak of approximately 15 ksi. The total affected depth is shallow being less than .004". Abusive grinding produces a residual stress profile which is very similar in appearance, but involving considerably deeper stresses having a higher tensile level. Peak stresses ranging from 80 to 110 ksi are associated with abusive grinding, while the total depth affected is about .007".

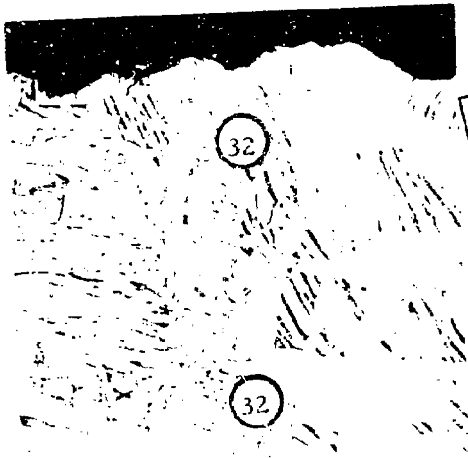
Low Cycle Fatigue Strength

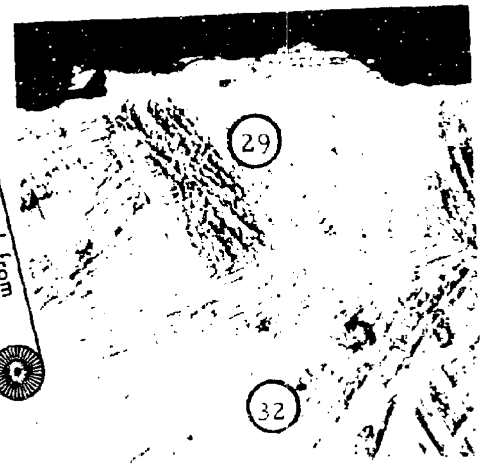
The low cycle fatigue behavior of this alloy is shown in Figure 47. Low cycle fatigue data are compared at the 20,000 cycle range. This is a standard which has been adopted for this program. At the 20,000 cycle level, the Ti-6Al-4V shows a reduction in stress from 92 ksi due to gentle grinding to 71 ksi due to abusive grinding, or a loss of 23 percent. In comparing cyclic lives at 92 ksi, gentle grinding yielded 20,000 cycles, while the life of the abusively ground material was approximately 10,500 cycles, or a loss of 48 percent. At somewhat higher test stresses which resulted in specimen lives of 3,000 to 4,000 cycles, the test points suggest that a crossover in behavior occurs.

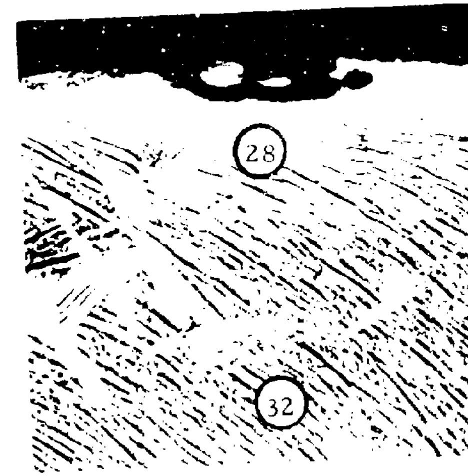
6.4.1 Surface Grinding - Ti-6Al-4V, Beta Rolled, 32 R_c (continued)

Low Cycle Fatigue Strength (continued)

In comparing this low cycle fatigue behavior with high cycle data previously obtained and shown in Figure 44, it may be concluded that the fatigue behavior becomes less sensitive to the surface condition of this alloy when testing is carried out at higher and higher stresses, hence resulting in lower and lower fatigue lives. Therefore, while at the 10^7 cycle level, the fatigue lives are different having a factor of 5:1, this gap appears to be continuously narrowing to the point where no effect at all is observed at stresses which permit only a 3,000 to 4,000 cycle life. A summary of individual test points is contained in Table XVI.







(a) Gentle Conditions
Surface Finish:
Perpendicular to lay: 35 AA
Parallel to lay: 14 AA

(b) Conventional Conditions
Surface Finish:
Perpendicular to lay: 45 AA
Parallel to lay: 18 AA

(c) Abusive Conditions
Surface Finish:
Perpendicular to lay: 65 AA
Parallel to lay: 26 AA

Gentle grinding produced no microstructural changes, although some degree of surface roughness is evident. Conventional and abusive grinding shows evidence of plastic deformation at the surface plus some tendency toward tearing. Both conventional and abusive grinding produced softening due to localized surface heating. Gentle grinding did not show this effect. Indicated hardness data are R_c values converted from Knoop microhardness measurements. Surface finish measurements are averages of readings made on all specimens from each group.

Magnification: 1000X

ORIENTATION: LONGITUDINAL GRIND. SURFACE SECTIONS PERPENDICULAR TO GRINDING LAY

Figure 45
SURFACE CHARACTERISTICS OF TITANIUM 6Al-4V (BETA ROLLED, 32 R_c)
PRODUCED BY SURFACE GRINDING

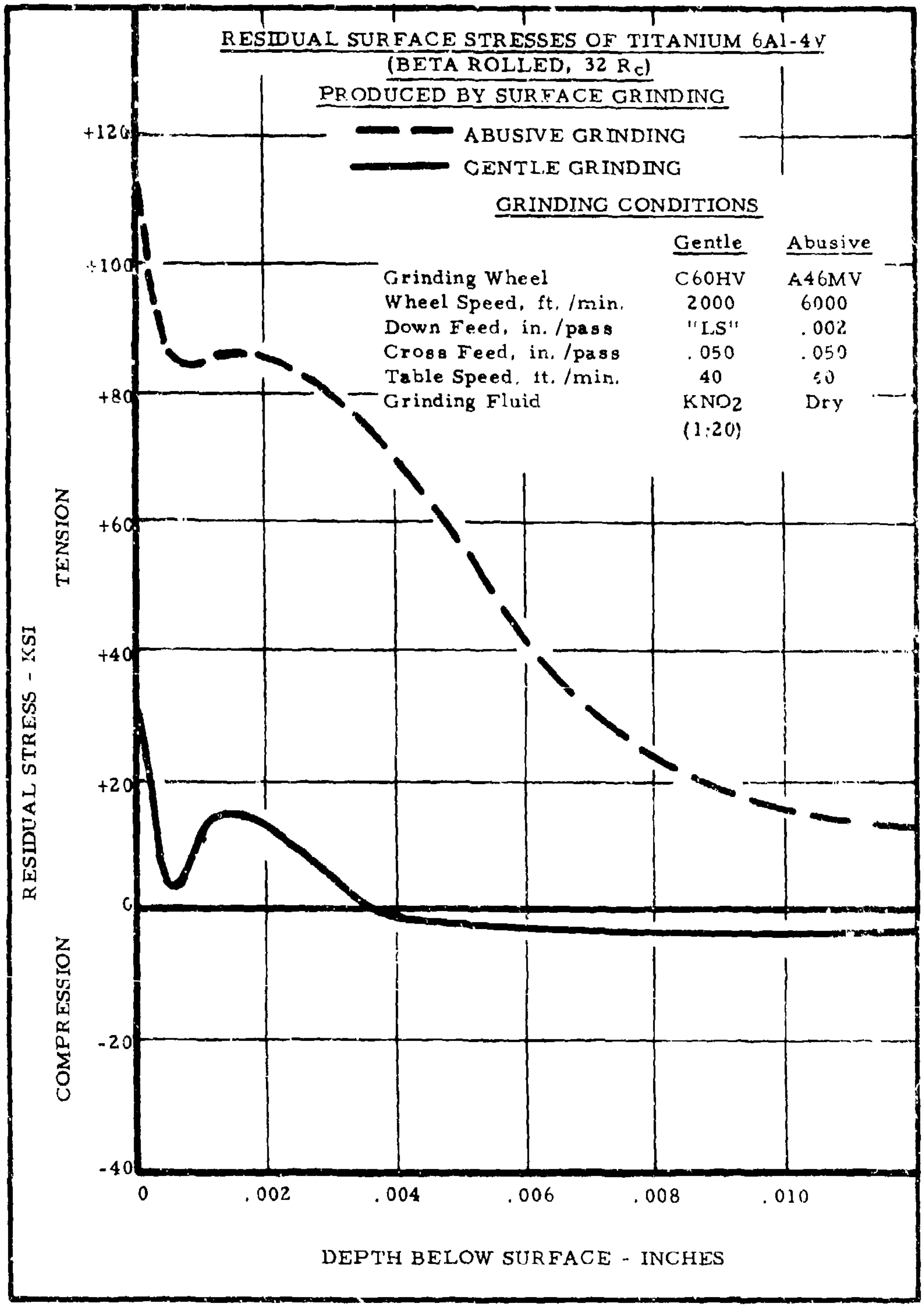


Figure 46
RESIDUAL STRESS IN TITANIUM 6Al-4V: SURFACE GRINDING

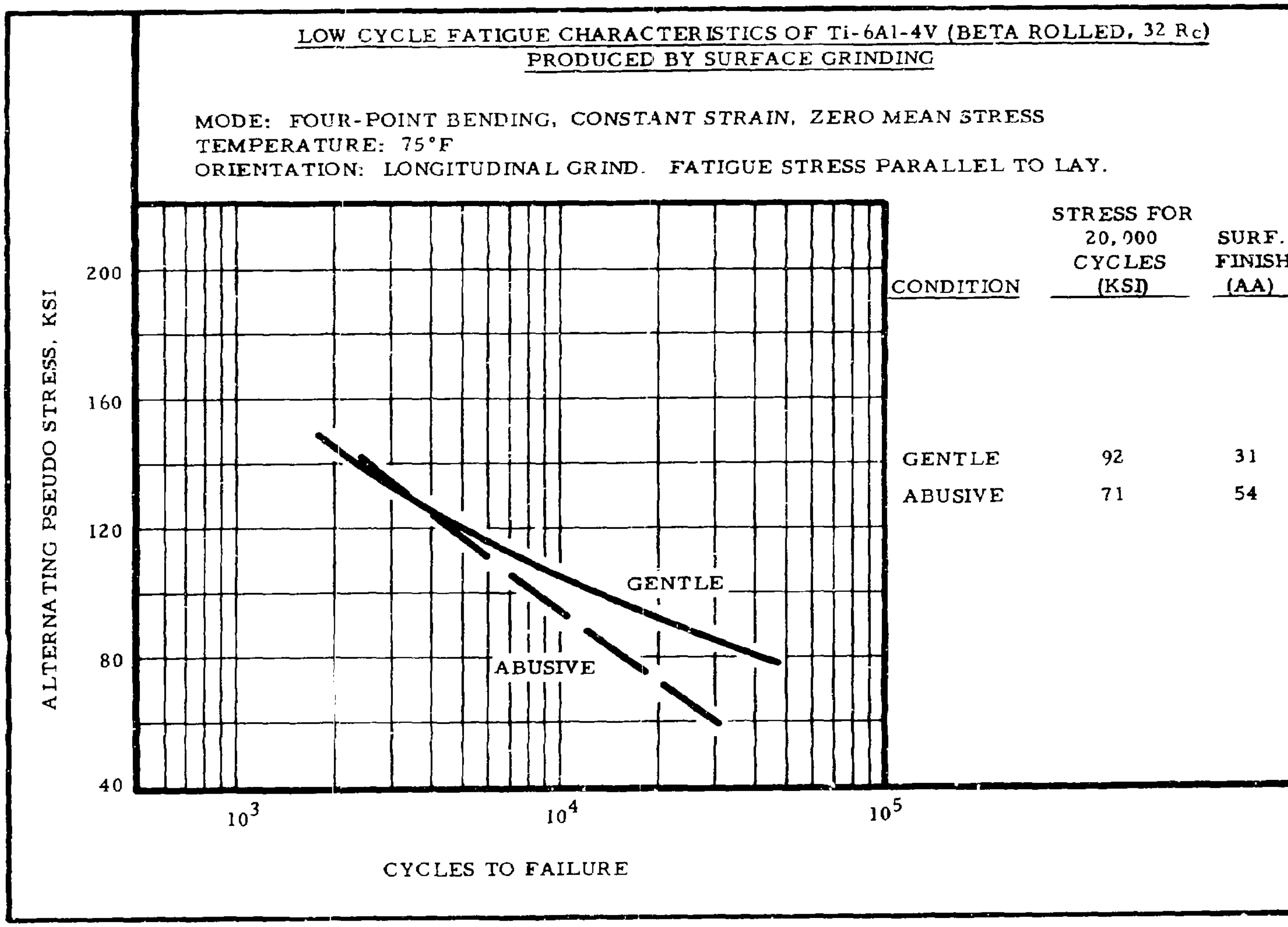


Figure 47
LOW CYCLE FATIGUE OF TITANIUM 6Al-4V: SURFACE GRINDING

6.4.2 End Milling-Peripheral Cutting - Ti-6Al-4V, Beta Rolled, 32 R_C

The surface integrity behavior of beta rolled Ti-6Al-4V finished by both end cutting and peripheral cutting was studied in detail in the previous contract, F33615-68-C-1003. A total of 20 different milling conditions were evaluated statistically to determine relative significance of various cutting parameters. Tool sharpness was found to be the most significant variable. The range of fatigue behavior resulting from the study is summarized in Figure 44. Since the peripheral cutting condition was found to be detrimental to fatigue life of this alloy under abusive conditions, a brief low cycle fatigue study was conducted in the present program. The metallographic and residual stress data which follows is extracted from previous reports in order to define the surface condition for which low cycle fatigue data was obtained and is reported herein.

Metallography

Photomicrographs of beta rolled Ti-6Al-4V produced by an arbitrary gentle and abusive condition are shown in Figure 48. As can be seen in these photomicrographs, no particular degree of surface distortion is visible. Likewise, microhardness data indicate no changes in the hardness of the surface layer. This behavior is typical of the beta rolled Ti-6Al-4V which has shown relatively little sensitivity either in terms of microstructural or hardness changes as a result of machining variables. Because the alloy is in the annealed condition, it appears to be much less sensitive to surface heating which occurs during machining than the other titanium alloys studied which were in the heat treated condition.

Residual Stress

The residual stress profiles obtained for this alloy under the milling conditions used for low cycle fatigue evaluation are shown in Figure 49. The gentle milling resulted in a shallow peak compressive stress of about 15 ksi, while the abusive milling produced an equally shallow peak tensile stress of approximately 30 ksi. The total effected depth in each case was .002 to .003". While some variation in residual stress profile pattern was noted in the detailed study mentioned above, residual stress curves shown in Figure 49 are fairly typical of the response to gentle and abusive peripheral end milling.

6.4.2 End Milling-Peripheral Cutting - Ti-6Al-4V, Beta Rolled, 32 R_c (continued)

Low Cycle Fatigue Strength

A summary of low cycle fatigue data for Ti-6Al-4V (beta rolled) machined by end milling-peripheral cutting is shown in Figure 50. In examining this figure, it is noted that the abusive condition provided a somewhat higher low cycle fatigue strength than the gentle milling condition. The stress to produce 20,000 cycles under abusive conditions was approximately 108 ksi, while the stress to produce the same life under gentle conditions was 98 ksi. Making a comparison at a constant stress level, the stress of 108 ksi which resulted in a 20,000 cycle life on the abusively milled surface yielded only a 12,900 cycle life on the gently milled surface.

In some situations, abusive end milling (end cutting) has been found to provide higher high cycle fatigue life than gentle milling (AMFL-TR-70-11). In the case of peripheral end milling on this particular alloy, however, a fatigue degradation was associated with abusive conditions. The reason for this reversing of behavior is not clear, but may be assumed to result from an interrelation of the surface plastic deformation resulting from the milling operation plus the superimposed plastic deformation due to the fatigue exposure.

Considering the overall behavior of this alloy, it appears most logical to conclude that the Ti-6Al-4V in the beta rolled condition has relatively low sensitivity to surface condition in the finite life or low cycle fatigue region. In contrast, however, very significant surface differences are found in high cycle fatigue life at 10^6 cycles and above. A summary of individual test points is contained in Table XVI.

(a) Gentle Milling
Surface Finish:
Perpendicular to lay: 31 AA
Parallel to lay: 41 AA

(b) Abusive Milling
Surface Finish:
Perpendicular to lay: 54 AA
Parallel to lay: 51 AA

Photomicrographs showing sections of surfaces cut under gentle and abusive conditions. Little if any, evidence of plastic deformation or surface alteration is evident in these structures. No differences in microhardness were detected. Indicated hardness data are R_c values converted from Knoop microhardness measurements. Surface finish measurements are averages of readings made on all specimens from each group.

Magnification: 1000X

ORIENTATION: LONGITUDINAL MILL. SURFACE SECTIONS PERPENDICULAR TO LAY.

Figure 48
SURFACE CHARACTERISTICS OF Ti-6Al-4V (BETA *ROLLED*, 32 R_c)
PRODUCED BY END MILLING - PERIPHERAL CUTTING

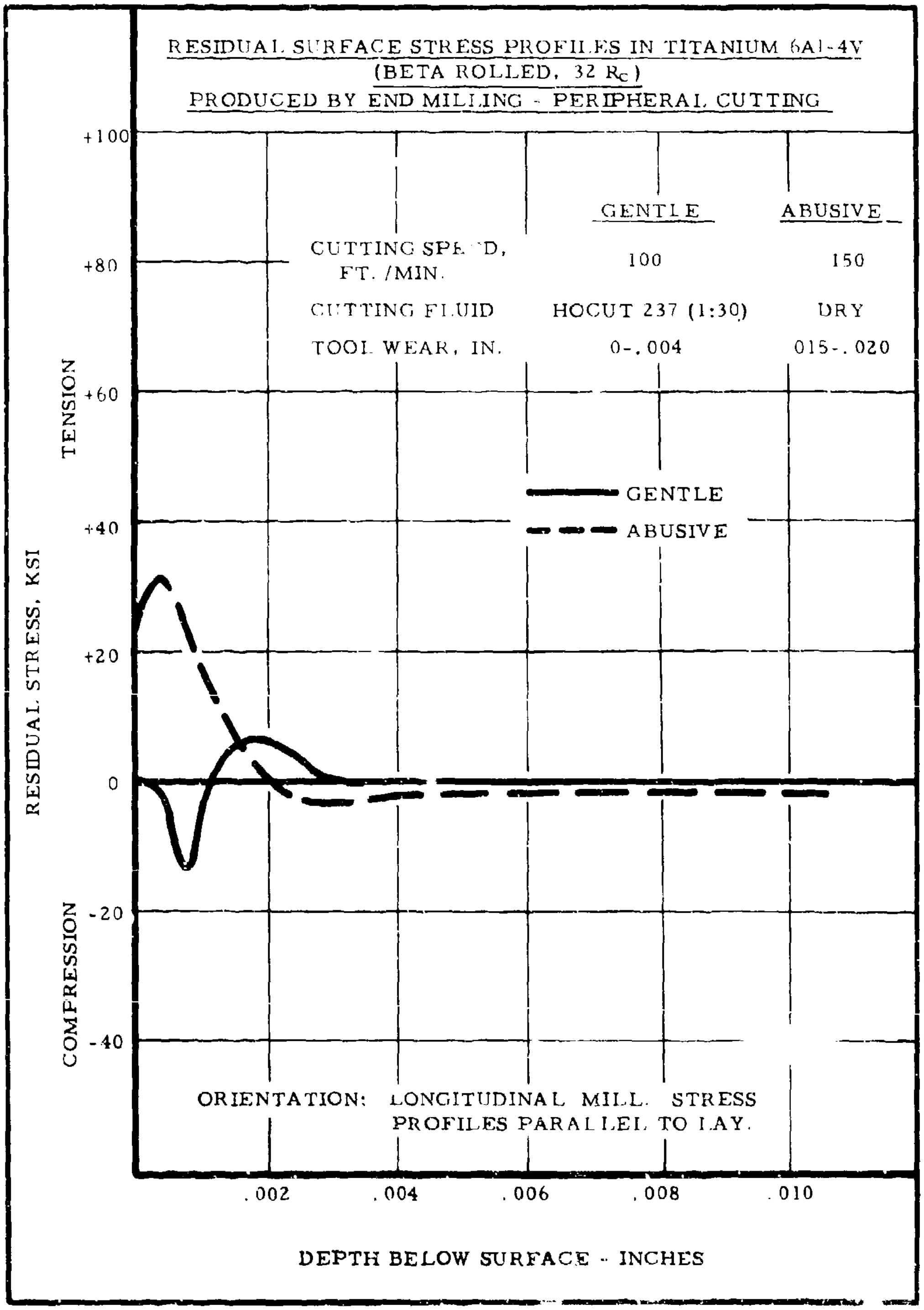


Figure 49
RESIDUAL STRESS IN TITANIUM 6Al-4V:
END MILLING - PERIPHERAL CUTTING

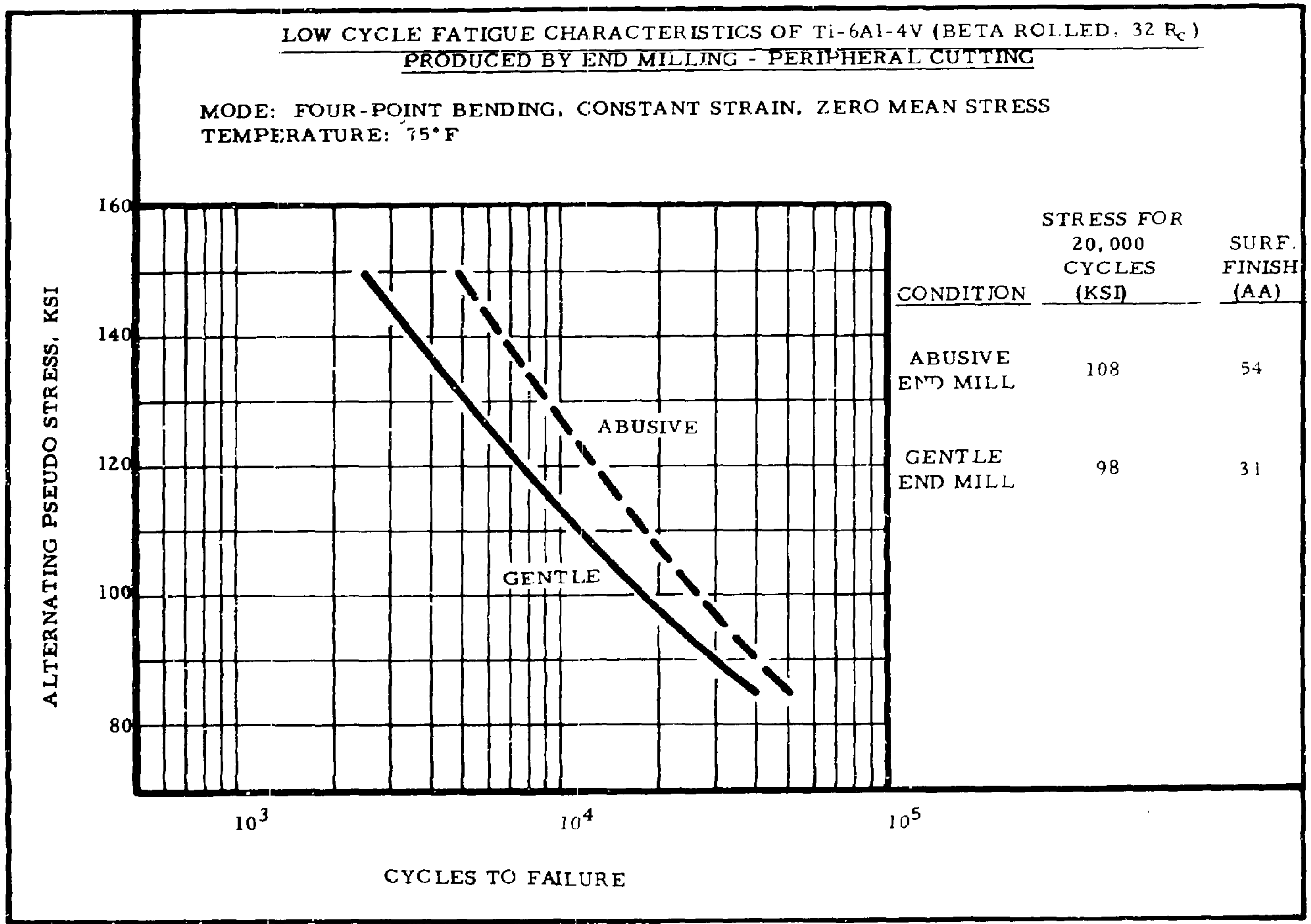


Figure 50
LOW CYCLE FATIGUE OF TITANIUM 6Al-4V:
END MILLING - PERIPHERAL CUTTING

6.5 Titanium 6Al-6V-2Sn, Solution Treated and Aged, 42 R_c

A summary of the low cycle and high cycle fatigue behavior of this alloy is contained in Figure 51. As can be seen, this titanium alloy is quite sensitive to processing variations when finished by surface grinding, end milling-end cutting, and ECM. The most pronounced effect was in the case of surface grinding where gentle versus abusive conditions resulted in corresponding fatigue strengths of 65 versus 20 ksi. Significant depressions, however, were also associated with abusive processing of end milling and ECM. An exception to this behavior was in the case of hand disc sanding which exhibited no difference between gentle and abusive processing in that the endurance limit associated with both conditions was 67 ksi.

Shot peening applied to the ECM surfaces was effective in overcoming the detrimental effects of abusive ECM in that the endurance limits of both the standard and off-standard ECM conditions were raised to 85 ksi. Peening was somewhat effective in overcoming damage due to the abusive grinding in that the endurance limit was raised from 20 to 50 ksi. But this did not approach the high value of 83 ksi exhibited by gentle grinding plus peening.

Low cycle fatigue behavior of Ti-6Al-6V-2Sn, also summarized in Figure 51, indicates that this material is relatively insensitive to surface variations under these test conditions. Differences between gentle and abusive conditions were of the order of 10 percent, and even though the trends were the same as for high cycle fatigue, the differences are sufficiently small as to be considered not particularly significant.

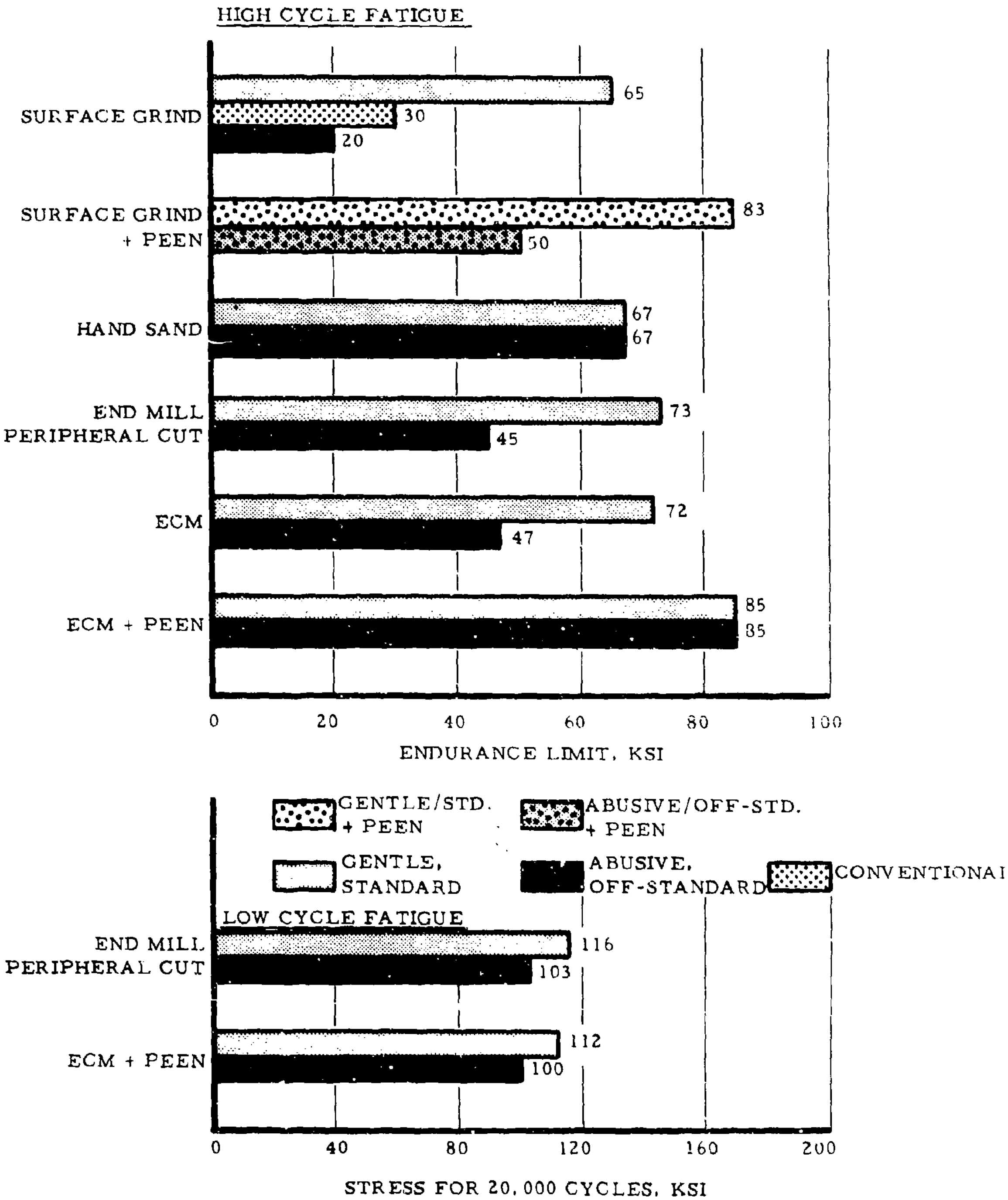


Figure 51
SUMMARY OF FATIGUE RESPONSE OF TI-6Al-6V-2Sn.
(SOLUTION TREATED AND AGED, 42 R_c)

6.5.1 Surface Grinding - Ti-6Al-6V-2Sn, STA, 42 R_c

Metallography

Test cuts used to obtain gentle, conventional, and abusive grinding conditions on this alloy are summarized in Table II. Photomicrographs of surface sections are shown in Figure 52. Gentle surface grinding shown in Figure 52 (a) exhibits a somewhat roughened surface but with no microstructural evidence of overheating or subsurface alteration. Extensive surface softening, however, gave a clear indication of surface damage probably due to localized heating even under gentle conditions. Very low surface microhardness measurements were obtained on gently ground samples with several readings in the range of 30 R_c at .0005 in. and 35 R_c at .001 inches. A slight peak in excess of the base hardness was observed at .003 in. below the surface. The same general microhardness pattern was observed under both conventional and abusive grinding conditions, but extending to a greater depth beneath the surface. In the case of abusive grinding, for example, a total affected depth of hardness loss of approximately .010 in. was noted.

The conventionally ground microstructure shows some evidence of surface alteration as indicated by a reasonably continuous white layer across the surface. A pronounced heat affected zone was produced by abusive grinding. Visually, the total affected depth of altered microstructure was approximately .006 in., although hardness changes were observed to a greater depth as noted above. This shows a marked sensitivity of the material to abusive surface grinding as judged from both the microstructure and the microhardness effect.

Photomicrographs showing ground samples which have also been subjected to shot peening are shown in Figure 53. Samples which have been gently and abusively ground are presented in this figure and appear to be very similar to those which illustrate the condition prior to shot peening, Figure 52. The same surface softening characteristics exist, although the extent of softening is not quite as great as in the unpeened surface. This may be a sample to sample difference or may be the result of a slight work hardening effect due to shot peening.

6.5.1 Surface Grinding - Ti-6Al-6V-2Sn, STA, 42 R_c (continued)

Residual Stress

All residual stress profiles associated with grinding contain high residual tensile stresses. Gentle, conventional, and abusive grinding exhibit peak tensile stresses of 20, 60, and 90 ksi, respectively. The abusive grinding produced the greatest depth effect. These various comparisons are indicated in Figure 54.

Residual stress profiles measured in Ti-6Al-6V-2Sn as a result of grinding followed by shot peening are shown in Figure 55. Notice that both types of ground surfaces exhibit peak compressive stresses in the range of 70-90 ksi. This behavior is typical of that which has been observed previously, namely, that shot peening will produce peak residual compressive stresses in a surface equal roughly to one half the yield strength of the material.

High Cycle Fatigue Strength

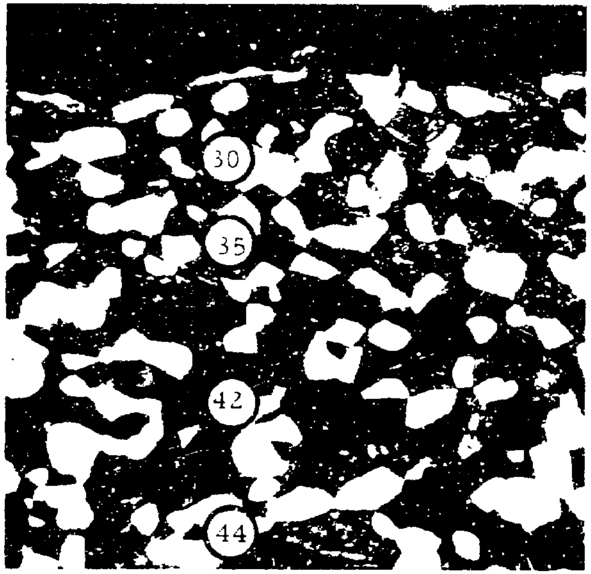
A summary of the fatigue behavior of Ti-6Al-6V-2Sn due to variables in grinding is shown in Figure 56. Complete data are contained in Table XVII. The endurance limit of 65 ksi associated with gentle grinding is within the normal range of properties to be expected from this material. Conventional and abusive grinding, however, exhibit marked depressions in fatigue strength to 30 and 20 ksi, respectively. This general behavior is typical of that which has been observed previously on Ti-6Al-4V. It is perhaps significant to note that these variations in fatigue strength bear no consistent relationship to the surface finish levels of these specimens which are also indicated in Figure 56.

Shot peening is effective in elevating the fatigue strength of ground Ti-6Al-6V-2Sn. Notice, however, also as indicated in Figure 56, that the fatigue strength on abusively ground surfaces was raised from 20 to 50 ksi, while the fatigue strength of gently ground surfaces was raised from 65 to 83 ksi. It is most important to notice that although approximately equal compressive stresses were produced in both the gently and abusively ground surfaces by shot peening, that the fatigue restoration was not equal. This is another one of many indications that residual stress alone will not be used as the sole criterion for predicting fatigue behavior. It is also an

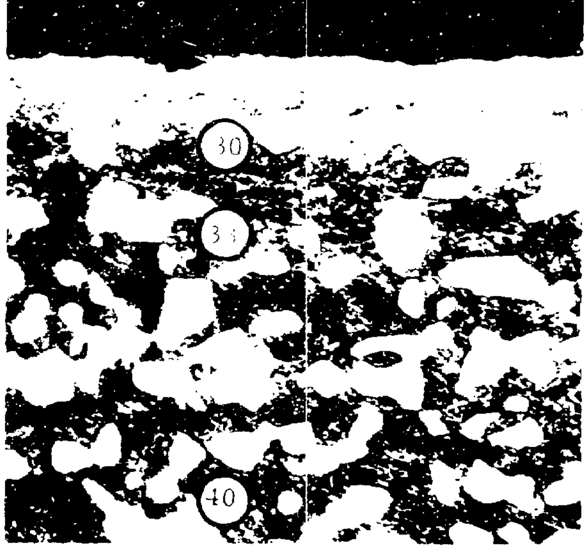
6.5.1 Surface Grinding - Ti-6Al-6V-2Sn, STA, 42 R_c (continued)

High Cycle Fatigue Strength (continued)

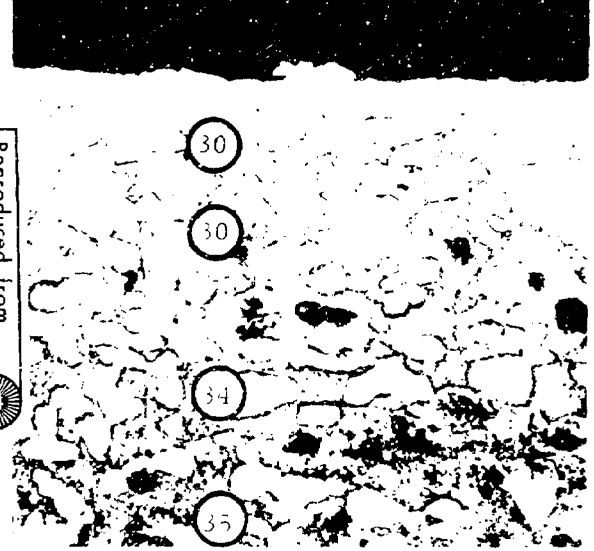
indication that, while helpful, shot peening is not completely effective in overcoming surface damage resulting from abusive grinding on this alloy.



(a) Gentle Grinding
Surface Finish:
Perpendicular to lay: 43 AA
Parallel to lay: 25 AA



(b) Conventional Grinding
Surface Finish:
Perpendicular to lay: 44 AA
Parallel to lay: 27 AA



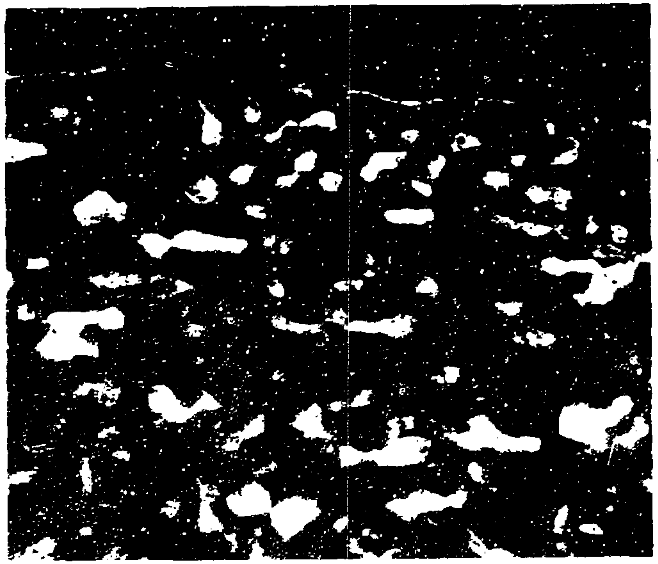
(c) Abusive Grinding
Surface Finish:
Perpendicular to lay: 70 AA
Parallel to lay: 40 AA

The microstructural response of Ti-6Al-6V-2Sn indicates a high sensitivity of this alloy to surface heating associated with abusive grinding. Abusive grinding produced large changes in structure as well as substantial hardness loss at the surface. The total depth to which the abusively ground structure was affected was .006 in. Hardness loss occurred up to a depth of .010 in. Gentle and conventional grinding exhibit minor surface effects, although both conditions underwent substantial hardness losses at the extreme surface as indicated. Hardness data are shown as R_c values converted from Knoop microhardness measurements. Surface finish measurements are the averages of readings made on all specimens from each group.

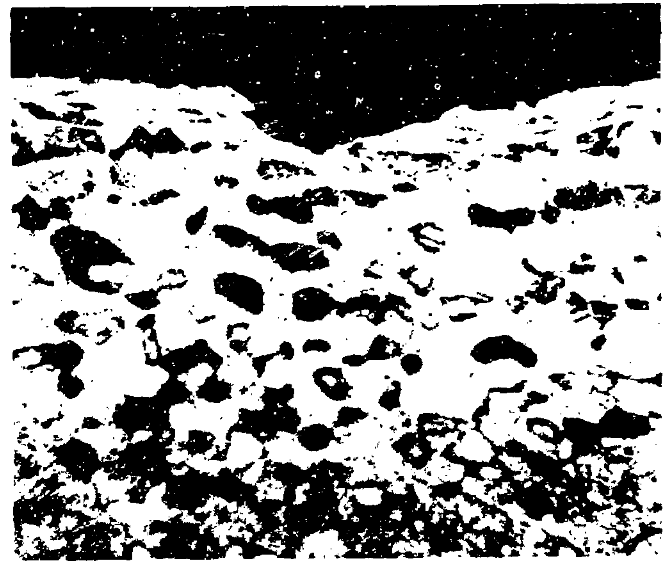
Magnifications: 1000X

ORIENTATION: LONGITUDINAL GRIND. SURFACE SECTIONS PERPENDICULAR TO GRINDING LAY.

Figure 52
SURFACE CHARACTERISTICS OF Ti-6Al-6V-2Sn (SOLUTION TREATED AND AGED, 42 R_c)
PRODUCED BY <u>SURFACE GRINDING</u>



Gentle Grinding
Surface Finish:
Perpendicular to lay: 43 AA
Parallel to lay: 40 AA



Abusive Grinding
Surface Finish:
Perpendicular to lay: 55 AA
Parallel to lay: 45 AA

Microstructures of Ti-6Al-6V-2Sn as a result of grinding followed by shot peening. The sensitivity of the alloy to surface heating during grinding is evidenced both by the microstructure in Figure 53 (b) and by the microhardness losses at the surface evident in both figures. No visual evidence of plastic deformation due to peening, however, can be seen. Indicated hardness data are R_c values converted from Knoop microhardness measurements. Surface finish measurements are averages of readings made on all specimens from each group.

ORIENTATION: LONGITUDINAL GRIND. SURFACE SECTIONS PERPENDICULAR TO GRINDING LAY.

Figure 53
SURFACE CHARACTERISTICS OF Ti-6Al-6V-2Sn (SOLUTION TREATED AND AGED, 42 R_c) PRODUCED BY SURFACE GRINDING PLUS PEENING

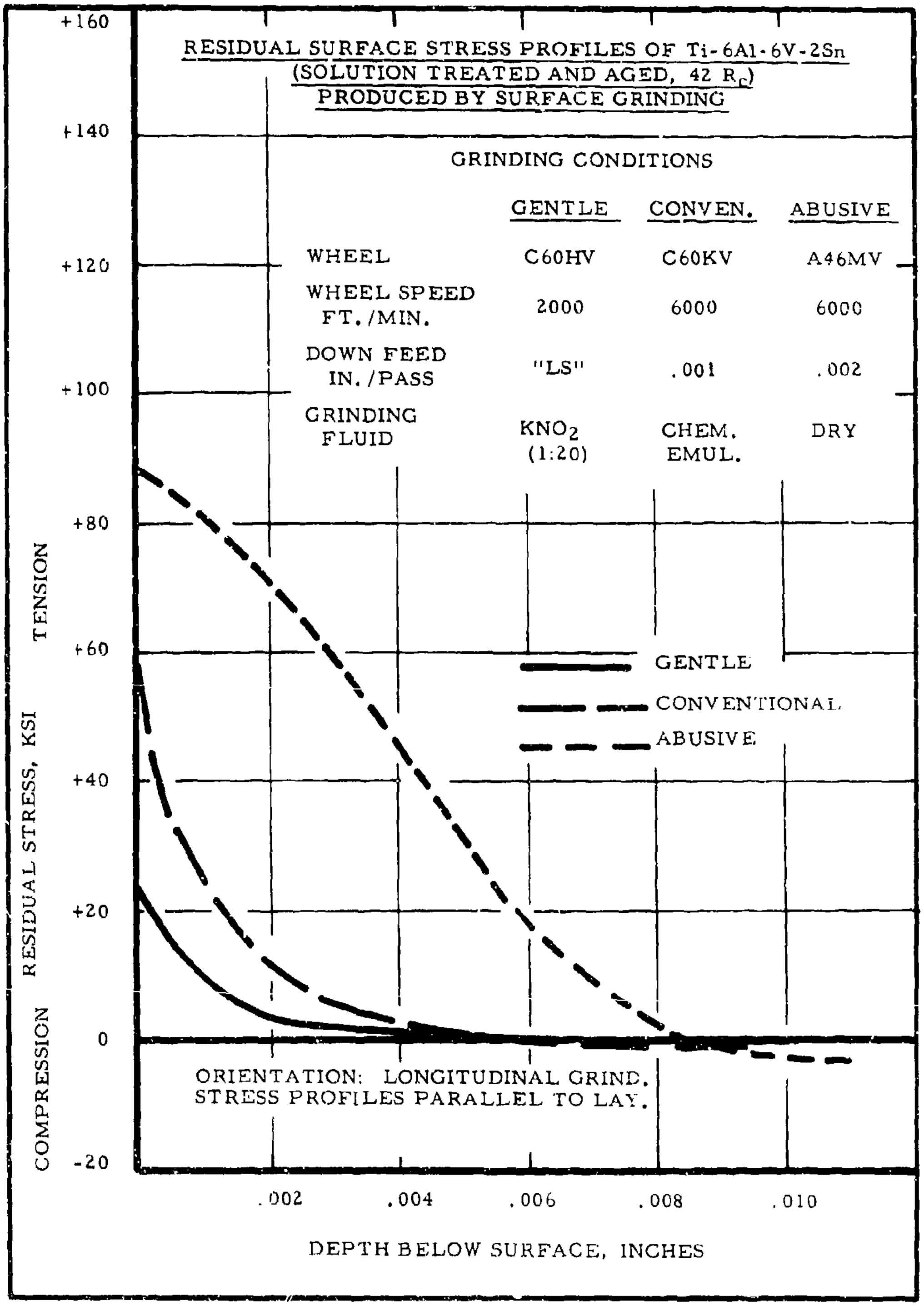


Figure 54
RESIDUAL STRESS IN TITANIUM 6Al-6V-2Sn: SURFACE GRINDING

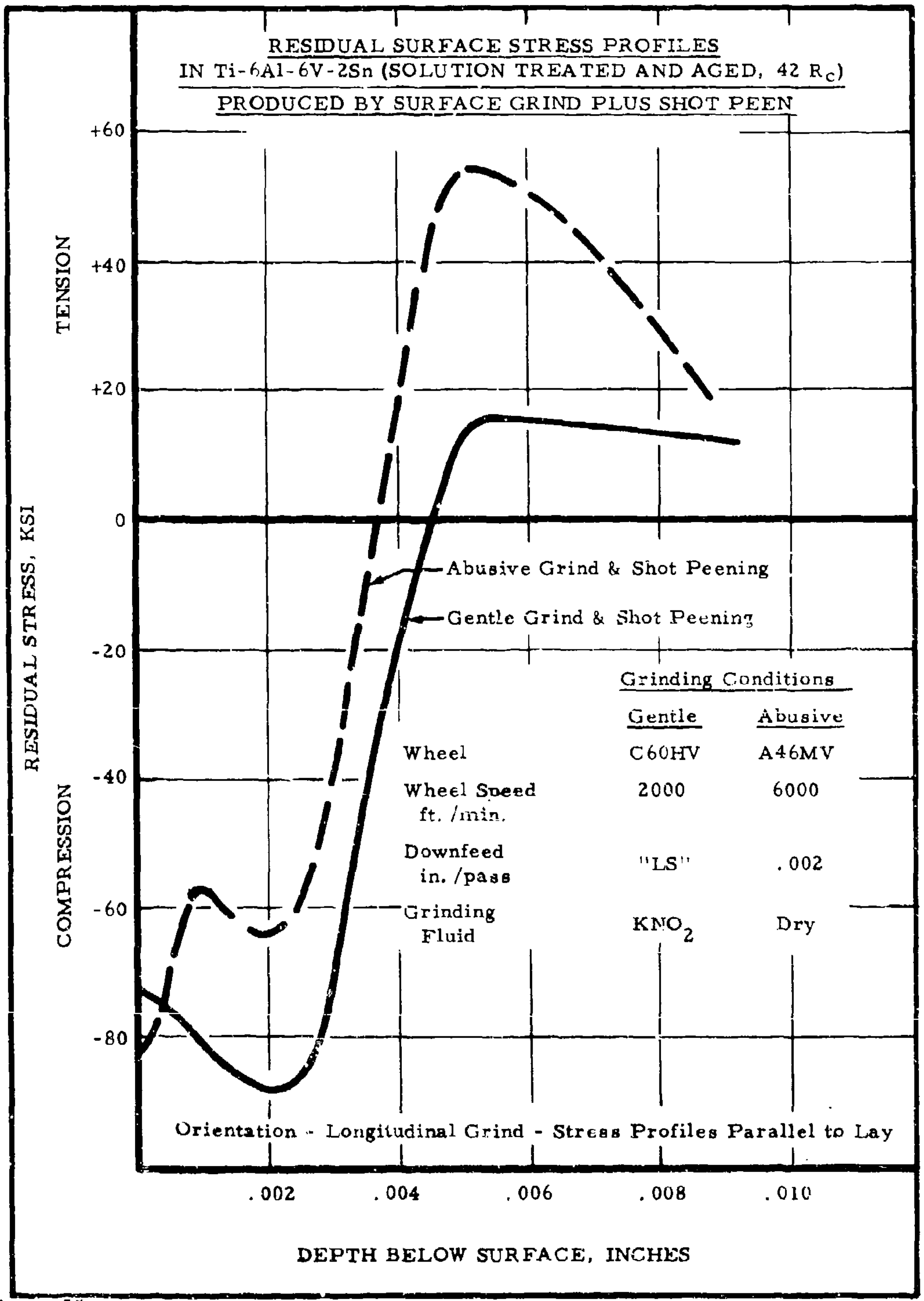


Figure 55
RESIDUAL STRESS IN TITANIUM 6Al-6V-2Sn: SURFACE GRIND PLUS SHOT PEEN

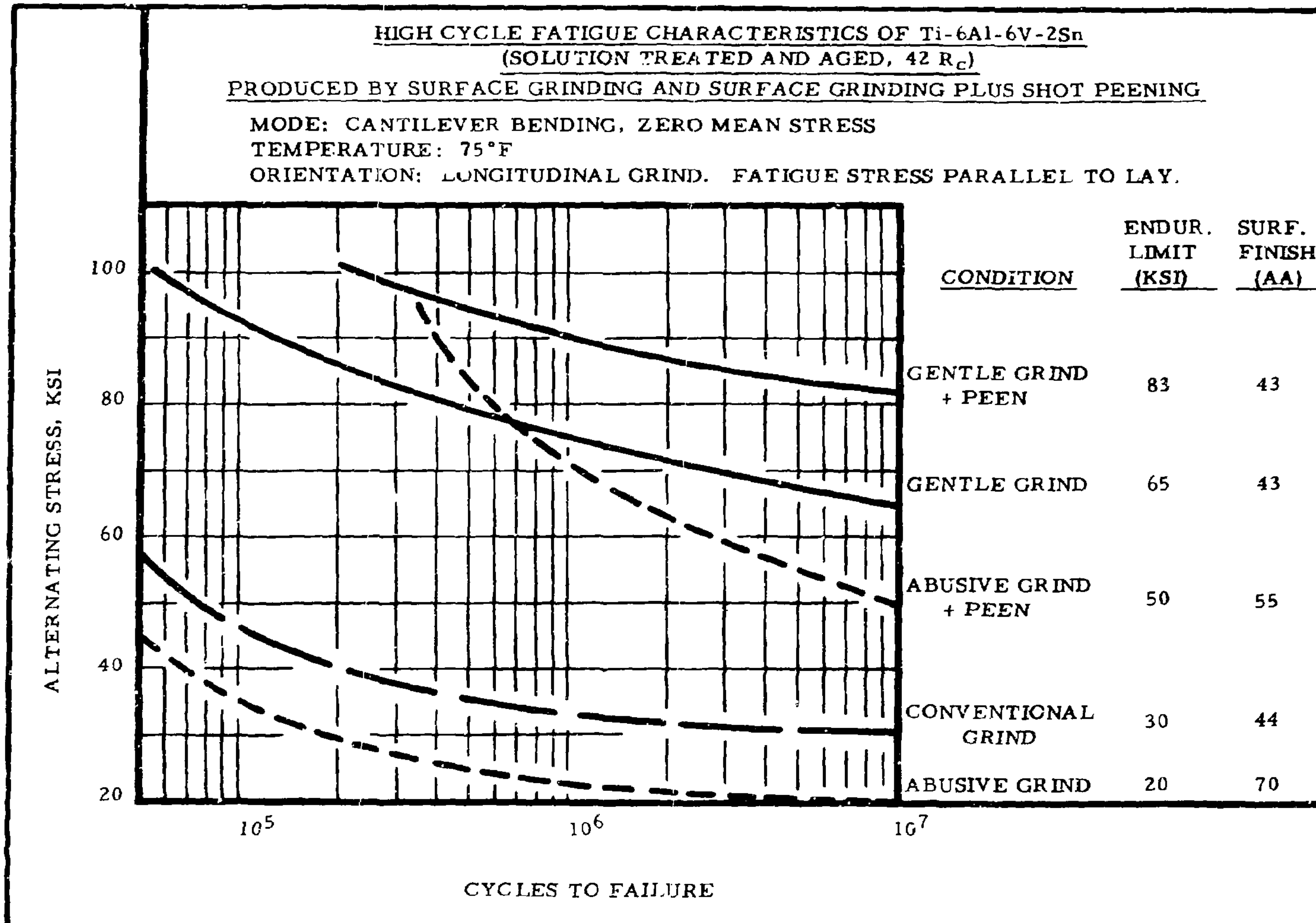


Figure 56
HIGH CYCLE FATIGUE OF TITANIUM 6Al-6V-2Sn:
SURFACE GRINDING AND SURFACE GRINDING PLUS SHOT PEENING

6.5.2 Hand Sanding - Ti-6Al-6V-2Sn, STA, 42 R_c

Metallography

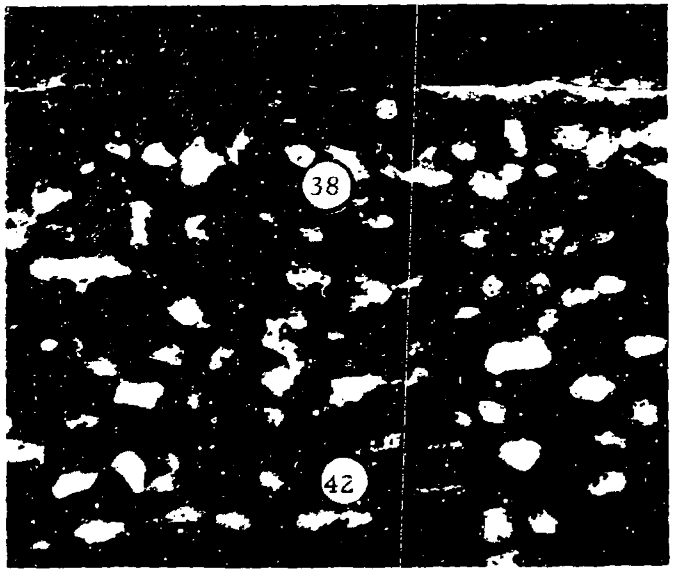
Photomicrographs of surface sections of this alloy produced by gentle and abusive hand sanding are shown in Figure 57. Disc sanding methods as summarized in Appendix I-3 and Table III were used to make these test cuts. The Ti-6Al-6V-2Sn alloy has demonstrated a microstructural sensitivity to localized surface heating as shown previously in the case of the microstructures resulting from surface grinding operations. Since the hand sanding shows very little if any microstructural change, it is assumed that relatively little surface heating was associated with the hand sanding operation. Some effect was noticed, however, since both samples exhibited a hardness loss of 4 points R_c, although the total depth effected in this was less than .002 inches.

Residual Stress

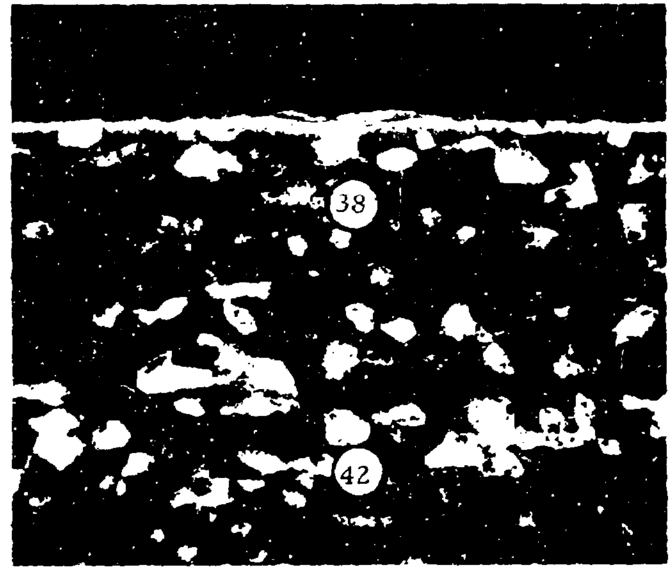
Residual stress profiles associated with hand sanding Ti-6Al-6V-2Sn are very similar resulting from both abusive and gentle conditions. Both curves, Figure 58, show a shallow compression and a subsequent surface tension, although at a low level of less than 10 ksi, approximately .004" beneath the surface. The level of compressive stress was slightly higher in the case of abusive sanding, although the position of the peaks was very similar. This behavior is quite in contrast to the residual stress profiles caused by surface sanding, Figure 53, which show very high tensile peaks for all conditions, even gentle sanding.

High Cycle Fatigue Strength

Both gentle and abusive surfaces exhibited the same high cycle fatigue strength, 67 ksi, as shown in Figure 59. This compares very favorably to the 65 ksi level which resulted from gentle surface grinding. Abusive hand sanding did not produce the marked fatigue depression which was attributed to abusive surface grinding. Comparing, however, the microstructures associated with the hand sanding and surface grinding operations, this behavior is not surprising in view of the minimum surface distortion produced by the abusive sanding operation. The individual fatigue data points are summarized in Table XVII.



(a) Gentle Sanding
Surface Finish
Perpendicular to lay: 14 AA
Parallel to lay: 15 AA



(b) Abusive Sanding
Surface Finish
Perpendicular to lay: 14 AA
Parallel to lay: 15 AA

Surface sections show relatively little influence from localized heating due to hand sanding operations. A thin white layer is evident on the abusively sanded sample. Thin discontinuous patches of the white layer may be seen on the gently sanded surface. Both samples exhibited a microhardness loss at the surface of approximately 4 points R_c, although the total affected depth of this softening was less than .002". Indicated hardness data are R_c values converted from Knoop microhardness measurements. Surface finish measurements are averages of readings made on all specimens from each group.

Magnification: 1000X

ORIENTATION: TRANSVERSE SAND. SURFACE SECTIONS PERPENDICULAR TO SANDING LAY.

Figure 57
SURFACE CHARACTERISTICS OF Ti-6Al-6V-2Sn (SOLUTION TREATED AND AGED, 42 R_c) PRODUCED BY HAND SANDING

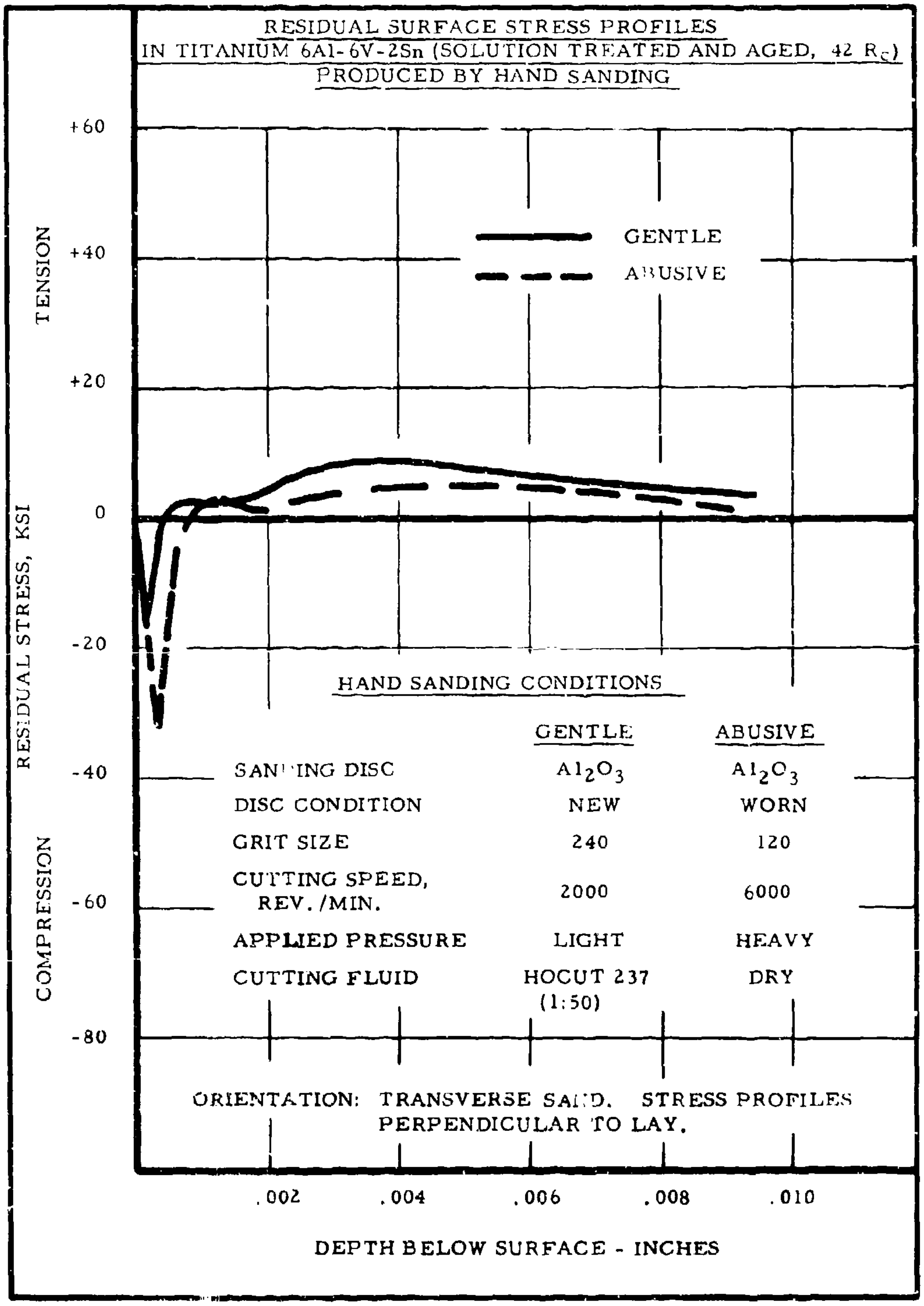
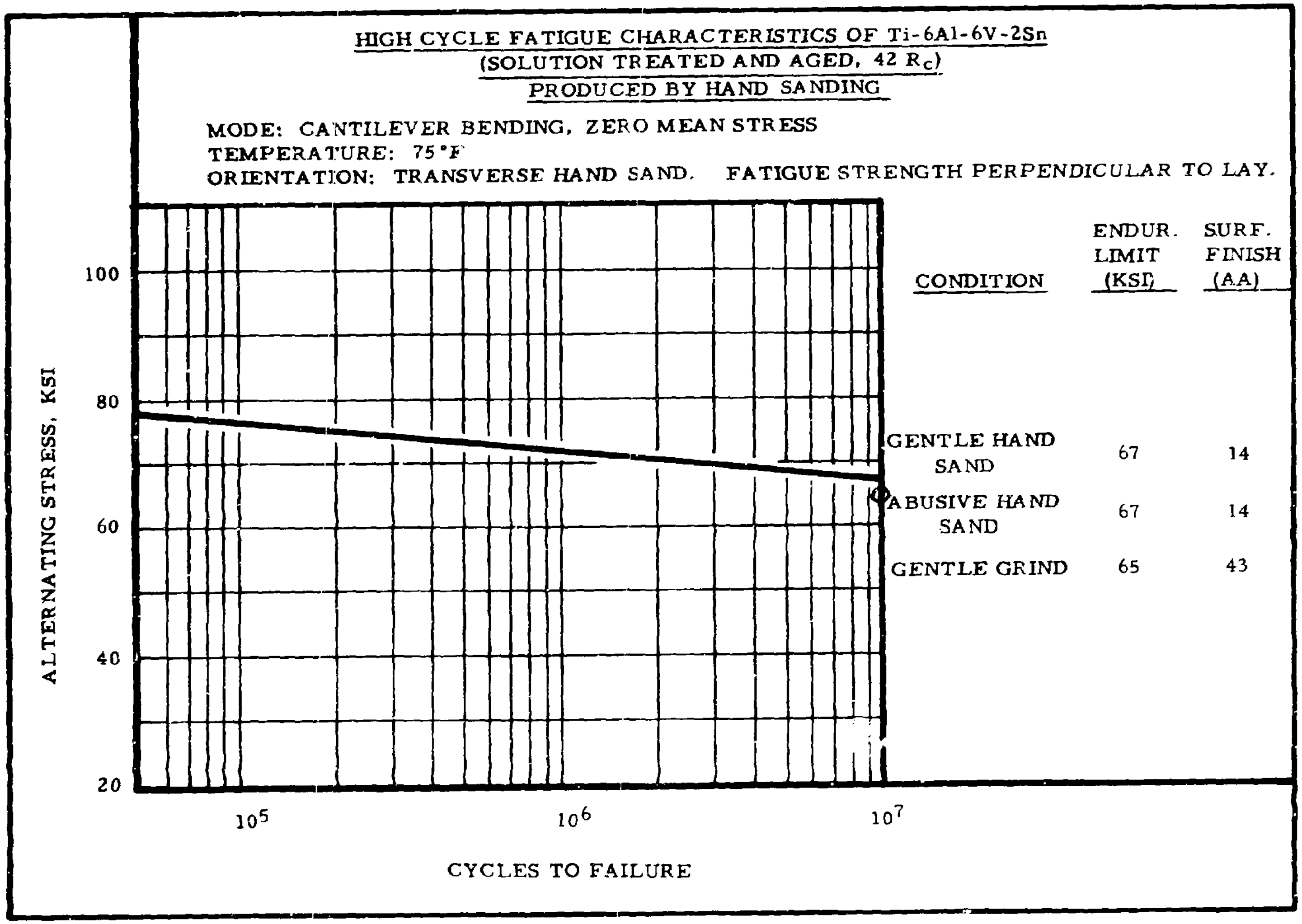


Figure 58
RESIDUAL STRESS IN TITANIUM 6Al-6V-2Sn: HAND SANDING



CONDITION	ENDUR. LIMIT (KSI)	SURF. FINISH (AA)
GENTLE HAND SAND	67	14
ABUSIVE HAND SAND	67	14
GENTLE GRIND	65	43

Figure 59
HIGH CYCLE FATIGUE OF TITANIUM 6Al-6V-2Sn: HAND SANDING

6.5.3 End Milling-Peripheral Cutting - Ti-6Al-6V-2Sn, STA, 42 R_C

Metallography

Sections of surfaces produced by gentle and abusive end milling-peripheral cutting of Ti-6Al-6V-2Sn are shown in Figure 60. A very thin layer of surface distortion not exceeding .0001 in. is associated with the gentle cutting condition. Slight surface softening to the extent of 6 points R_C was measured at .0005 in. beneath the surface. The hardness change, however, completely disappeared in the gently milled surface at a depth of .002 inches.

When abusively milled, however, this alloy exhibited a rather pronounced surface reaction as shown in Figure 60 (b). A white layer, approximately .001 in. deep, was formed and an alteration in the structure could be seen for a total depth of .004 inches. Abusive milling resulted in a surface hardness loss of as much as 8 points R_C and a total affected depth of .004 inches. The microstructural conditions shown in Figure 60 (b) are primarily due to localized surface heating, although plastic deformation is also evident in the first .001 in. beneath the surface.

The milling conditions used for making the test cuts on these specimens are summarized in Table V.

Residual Stress

Residual stress profiles which were determined on Ti-6Al-6V-2Sn are shown in Figure 61. Both milling conditions showed evidence of surface tension. Gentle versus abusive milling produced surface stresses of 15 and 65 ksi, respectively. Both milling conditions also exhibited relatively low level subsurface compressive peaks. This behavior is somewhat different from that normally found as a result of milling. More typically, low residual surface stresses resulting from milling are compressive. Furthermore, they normally reach considerably higher levels than those exhibited by this alloy.

High Cycle Fatigue Strength

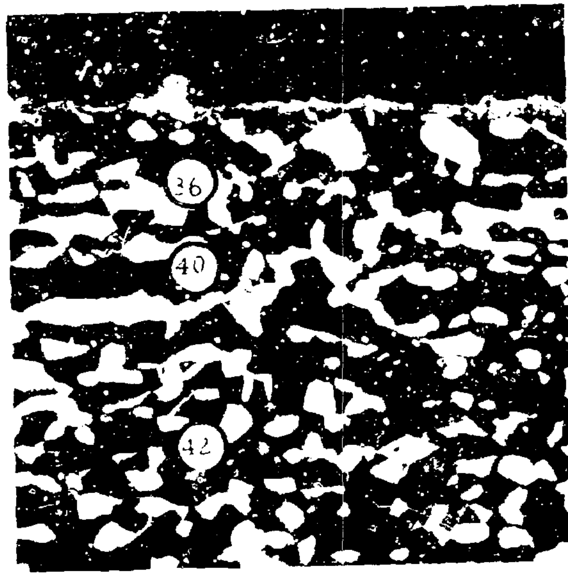
Fatigue strengths associated with milled Ti-6Al-6V-2Sn are shown in Figure 62. Gentle milling produced an endurance limit of 73 ksi, while abusive milling depressed this property to 45 ksi. These values may be compared to the gentle grinding baseline of 65 ksi. Data are summarized in Table XVII.

6.5.3 End Milling-Peripheral Cutting - Ti-6Al-6V-2Sn, STA, 42 R_c (continued)

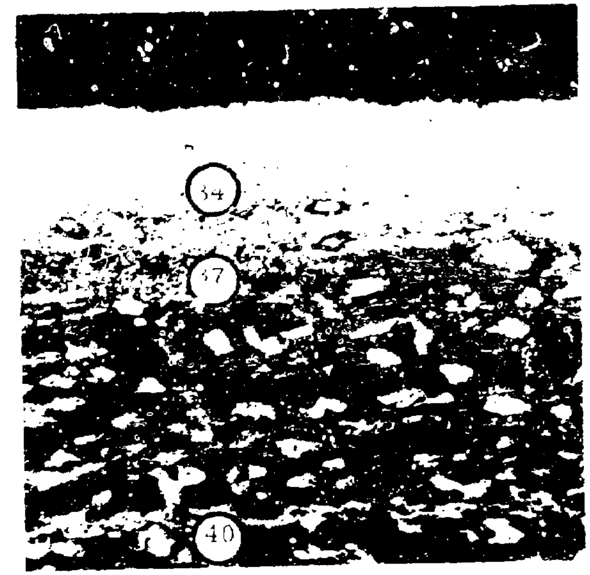
Low Cycle Fatigue Strength

Low cycle fatigue behavior of Ti-6Al-6V-2Sn at room temperature as the result of gentle and abusive peripheral end milling is summarized in Figure 63. The data show relatively little difference in behavior from the two different milling conditions, although some spread is indicated in the longer life tests. At 20,000 cycles, which has been adopted as a comparison standard for this program, the pseudo-stress values associated with gentle and abusive milling are 116 and 103 ksi, respectively. These data indicate an 11 percent drop in low cycle fatigue strength at 20,000 cycles for the abusive condition. Comparing cycle lives at 116 ksi, gentle versus abusive milling results in 20,000 versus 15,000 cycles, respectively or a life loss of 25 percent.

Machining conditions used to produce test cuts on these samples are summarized in Table V. Individual test results are presented in Table XVIII.



(a) Gentle Milling
Surface Finish:
Perpendicular to lay: 28 AA
Parallel to lay: 38 AA



(b) Abusive Milling
Surface Finish:
Perpendicular to lay: 39 AA
Parallel to lay: 32 AA

Slight evidence of distortion can be seen on the gently milled sample. Very pronounced alterations are associated with abusive milling. A maximum hardness loss of 8 points R_c and a total affected depth of .004 in. can be attributed to abusive milling. Approximately 6 points R_c surface hardness loss was measured on the gently milled samples. In this case, however, the effect was much shallower, not exceeding .002 in. Indicated hardness data on the photomicrographs are R_c values converted from Knoop microhardness measurements. Surface finish measurements are averages of readings made on all specimens from each group.

Magnifications: 1000X

ORIENTATION: LONGITUDINAL MILL. SURFACE SECTIONS PERPENDICULAR TO LAY.

Figure 60
SURFACE CHARACTERISTICS OF Ti-6Al-6V-2Sn (SOLUTION TREATED AND AGED, 42 R_c)
PRODUCED BY <u>END MILLING - PERIPHERAL CUTTING</u>

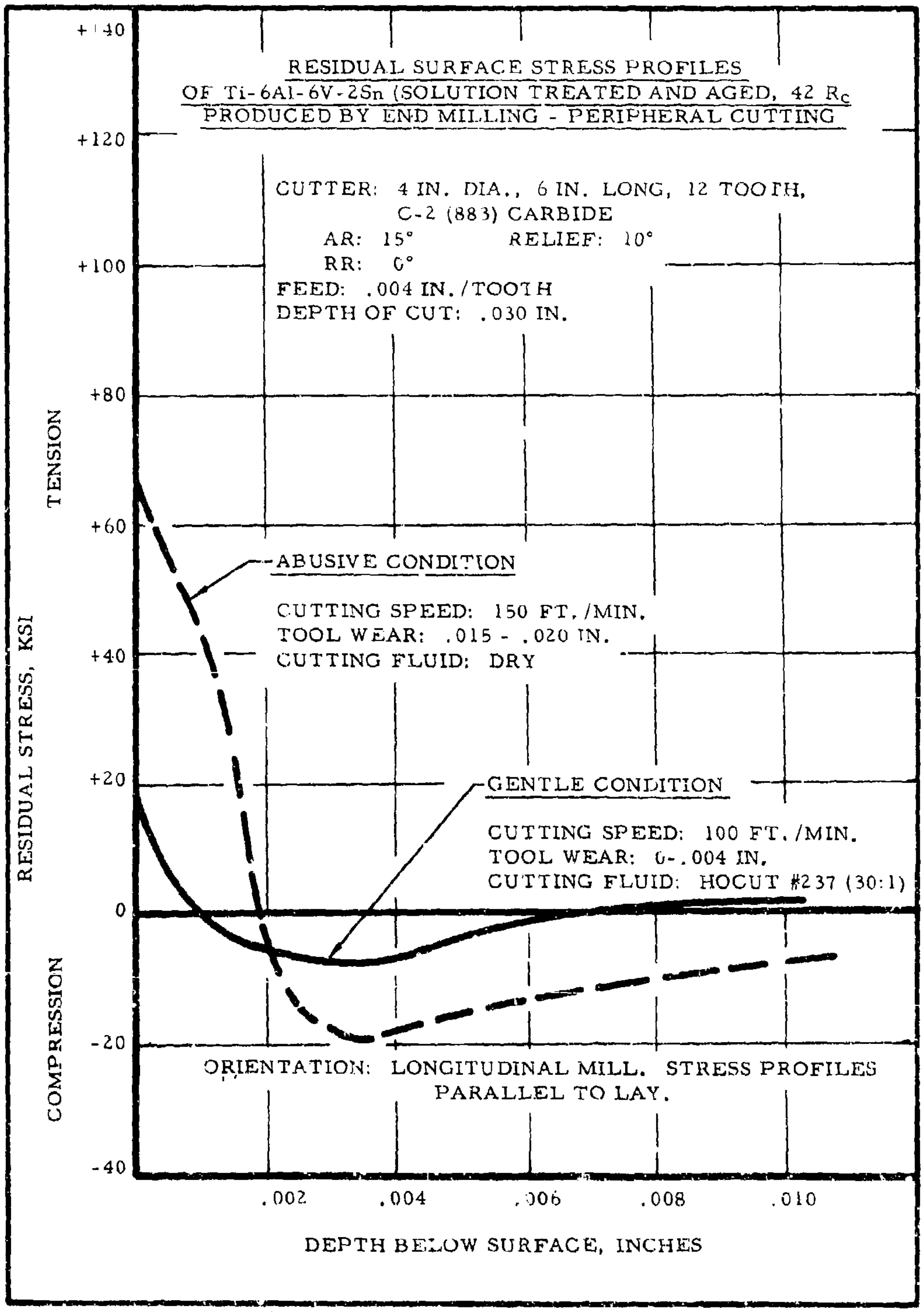


Figure 61
RESIDUAL STRESS IN TITANIUM 6Al-6V-2Sn:
END MILLING - PERIPHERAL CUTTING

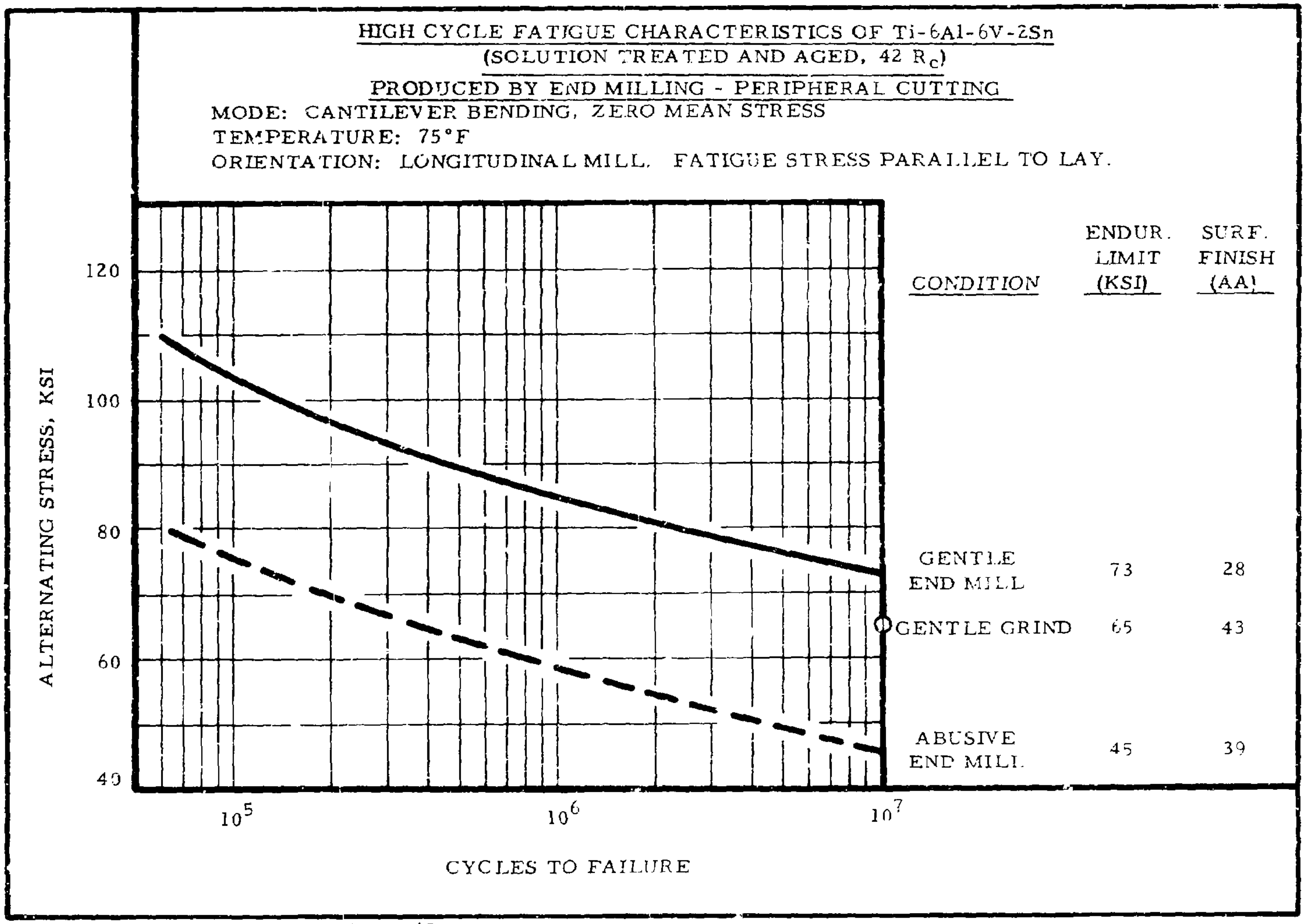
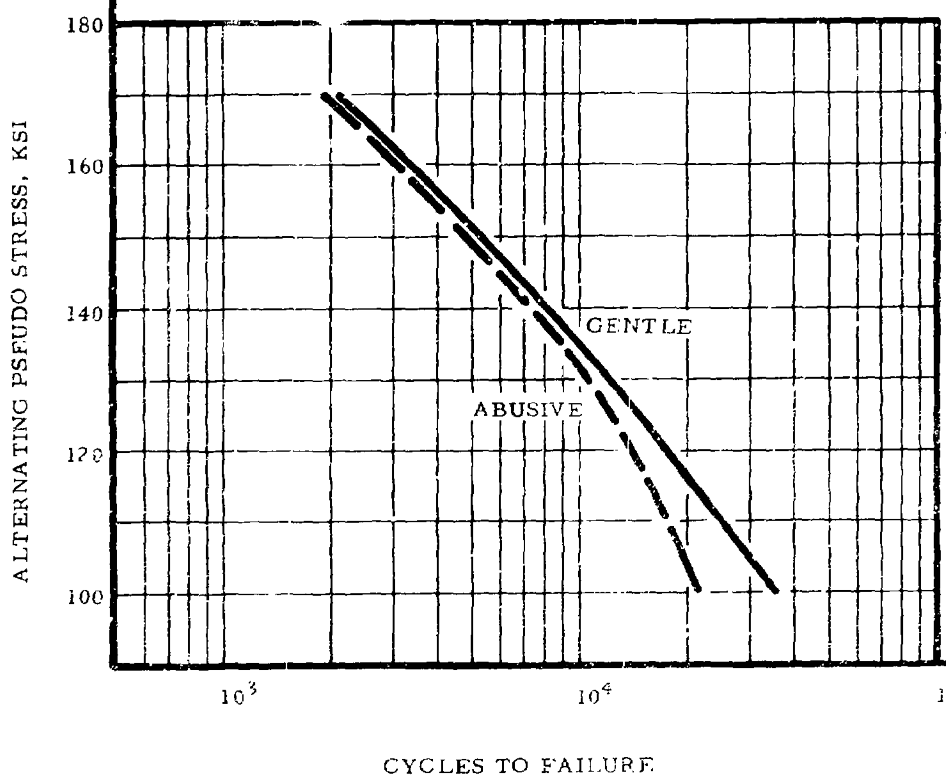


Figure 62
HIGH CYCLE FATIGUE OF TITANIUM 6Al-6V-2Sn:
END MILLING - PERIPHERAL CUTTING

LOW CYCLE FATIGUE CHARACTERISTICS OF Ti-6Al-6V-2Sn
(SOLUTION TREATED AND AGED, 42 R_c)
PRODUCED BY END MILLING - PERIPHERAL CUTTING

MODE: FOUR-POINT BENDING, CONSTANT STRAIN, ZERO MEAN STRESS
TEMPERATURE: 75°
ORIENTATION: LONGITUDINAL MILL. FATIGUE STRESS PARALLEL TO LAY



CONDITION	STRESS FOR 20,000 CYCLES (KSI)	SURF. FINISH (AA)
GENTLE END MILL	116	30
ABUSIVE END MILL	103	32

Figure 63
LOW CYCLE FATIGUE OF TITANIUM 6Al-6V-2Sn:
END MILLING - PERIPHERAL CUTTING

6.5.4 ECM - Ti-6Al-6v-2Sn, STA, 42 R_c

Metallography

Photomicrographs of structures resulting from the electrochemical machining of Ti-6Al-6V-2Sn under standard and off-standard conditions are shown in Figure 64. The ECM conditions used to produce these cuts are summarized in Table IX.

A cross section of the surface produced under standard ECM conditions shows no evidence of plastic deformation or other distortion. Microhardness data suggests a slight softening of the surface approximating two points R_c. This surface softening is typical of that which has been observed as a result of ECM.

The off-standard cutting condition resulted in a considerably rougher surface than the standard condition, 145 versus 11 AA, as indicated in Figure 64. This is the only visible difference resulting from standard versus off-standard ECM in that microhardness changes in both cases were about the same.

Photomicrographs of similar ECM surfaces, but modified by a post-processing shot peening are show in Figure 65. Shot peening conditions are summarized in Table IX. The photomicrographs show the same general conditions as indicated in Figure 65. No visual indication confirming the presence of the shot peening can be seen in this photomicrograph. This indicates that the actual degree of plastic deformation produced by the shot peening is relatively low. Were a large amount of plastic deformation present even in a very shallow layer, it would be quite evident.

Residual Stress

A summary of the residual stress data obtained on the four ECM conditions studied for this alloy is shown in Figure 66. Note that the standard and off-standard conditions in the as-ECM'd surface produce very low levels of residual stress. The peak stress measured is approximately 10 ksi tension at the surface.

6.5.4 ECM - Ti-6Al-6V-2Sn, STA, 42 R_c (continued)

Residual Stress (continued)

In contrast, the post-shot peening operation produced fairly high residual compression in the surface of about 80 ksi. The total effected depth was about .008 inches. The post-shot peened behavior of both the standard and the off-standard ECM'd specimens was about the same, hence, only a single profile is shown. This is to be expected since the as-ECM'd samples also showed essentially the same residual stress profile. The level of residual stress is also what might be expected in that many investigators have found that shot peening a surface will produce peak residual compressive stresses equal to about one-half the yield strength of the material being peened.

It is interesting to note that these large levels of residual stress are produced in the surface from the degree of plastic deformation produced by peening and yet the amount of deformation is sufficiently small as not to be easily detectable by optical metallographic techniques.

High Cycle Fatigue Strength

Fatigue behavior of Ti-6Al-6V-2Sn associated with ECM surfaces is shown in Figure 67. Samples finished by standard ECM exhibited an endurance limit (10^7 cycles) of approximately 72 ksi. This compares very favorably to the endurance limit of 65 ksi previously obtained for this same alloy finished by gentle grinding. This is the sole instance observed to date with any material where the fatigue strength due to ECM was higher than that due to gentle grinding.

Off-standard ECM, however, as may be seen in Figure 67, caused a marked reduction in fatigue strength to approximately 47 ksi. Since the residual stress profiles and the microhardness distribution in both the standard and the off-standard samples are about the same, this fatigue depression due to off-standard ECM may at least in part be attributable to the increased surface roughness. It may be misleading, however, to conclude that the difference is totally attributable to an increase in roughness since other factors may also contribute to this behavior. This alloy differs from the behavior of others studied in that in this case only, different ECM conditions result in significantly different fatigue properties.

6.5.4 ECM - Ti-6Al-6V-2Sn, STA, 42 R_C (continued)

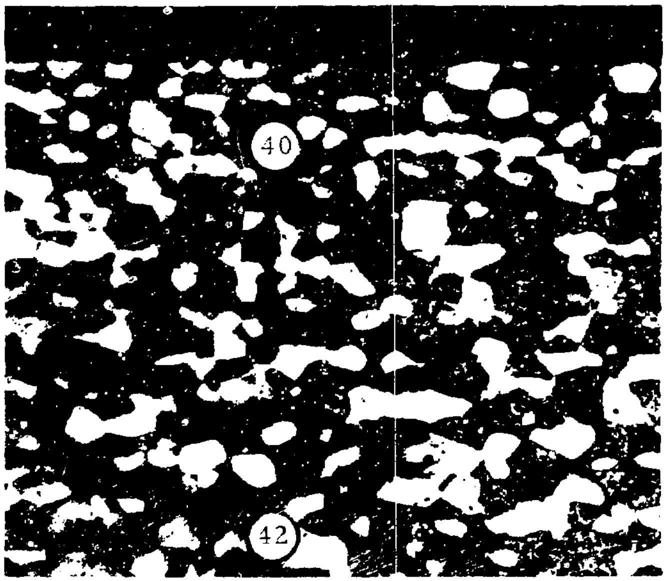
High Cycle Fatigue Strength (continued)

Shot peening of all of the samples under conditions shown in Table XI has resulted in a considerable increase in fatigue strength. Shot peening samples previously cut by both standard and off-standard ECM exhibited essentially the same behavior resulting in an endurance limit of about 85 ksi. It can be assumed that at least a portion of this fatigue elevation is due to residual compressive stresses induced by the peening operation.

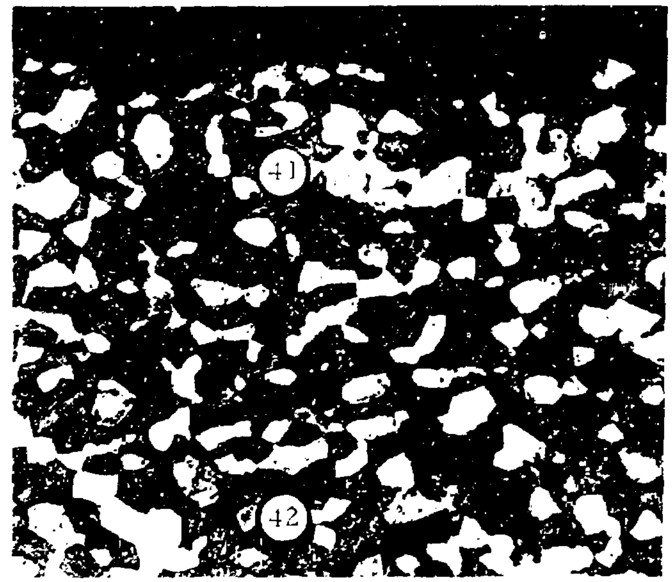
A summary of all of the fatigue data developed under this contract on Ti-6Al-6V-2Sn to date is contained in Table XVII.

Low Cycle Fatigue Strength

Low cycle fatigue behavior of this alloy after ECM and shot peening is shown in Figure 68. The stresses resulting in a 20,000 cycle life as a result of off-standard versus standard ECM were 100 to 112 ksi, respectively. This is particularly interesting behavior when a comparison is made to the high cycle results, Figure 67. In the case of the high cycle fatigue samples which were not peened, the off-standard ECM showed a pronounced fatigue depression compared to standard ECM, 47 versus 72 ksi. As a result of shot peening, the endurance limits of both ECM varieties were raised to 85 ksi. In the low cycle region, however, a separation between the standard and off-standard surfaces is again evident even though the same "corrective" peening had been applied to both surfaces as a post-processing operation. While the cause for this behavior is not completely clear, it is possible that the surface plastic strain magnitude of the high cycle fatigue testing exposure serves to relax, hence, partially overcome, the compressive stresses produced by peening. Should this be the case, the separation between standard and off-standard ECM strength as observed would again be evident. A summary of this data is presented in Table XVIII.



(a) Standard Conditions
Surface Finish: 11 AA

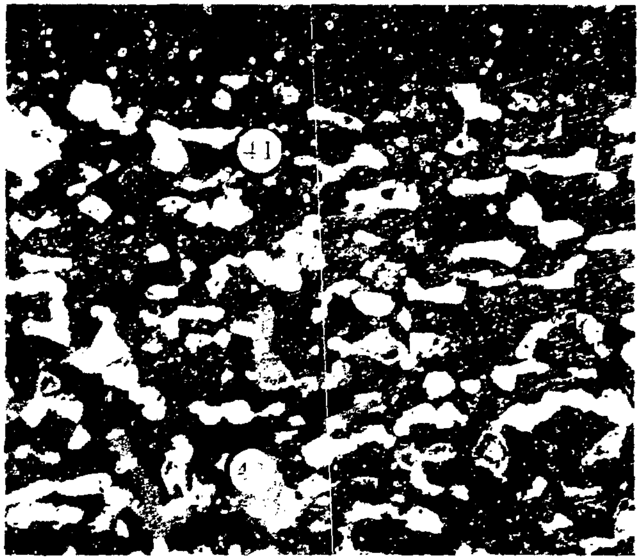


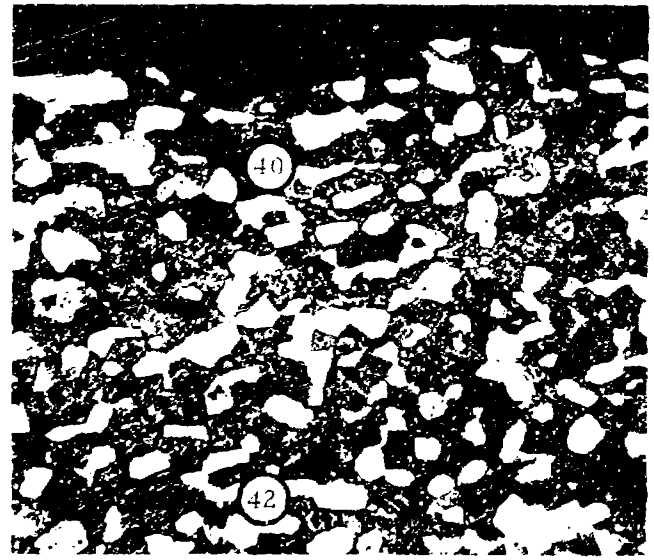
(b) Off-Standard Conditions
Surface Finish: 145 AA

No evidence of surface alteration or overheating is shown in the microstructures. Microhardness data indicate a softening of one to two points R_C at the first .001 in. beneath the surface. The only significant visible difference is the increased surface roughness due to off-standard conditions which can be readily seen above. Indicated hardness data are R_C values converted from Knoop microhardness measurements. Surface finish measurements are averages of readings made on all specimens from each group.

Magnifications: 1000X

Figure 64
SURFACE CHARACTERISTICS OF Ti-6Al-6V-2Sn (SOLUTION TREATED AND AGED, 42 R_C)
PRODUCED BY ECM





...dard Conditions
Surface Finish: 48 AA

(b) Off-Standard Conditions
Surface Finish: 120 AA

No evidence of surface damage is observed. The only visible difference between the two samples is the difference in surface roughness. The addition of shot peening to the surface did not result in plastic deformation of a degree which is visible in the microstructure. A slight surface softening to the extent of one to two points R_C was observed at the first .002 in. beneath the surface. This is the same as was observed for the unpeened condition indicating that peening caused no significant change in surface microhardness. Indicated hardness data are R_C values converted from Knoop microhardness measurements. Surface finish measurements are averages of readings made on all specimens from each group.

Magnification: 1000X

Figure 65
SURFACE CHARACTERISTICS OF Ti-6Al-6V-2Sn (SOLUTION TREATED AND AGED, 42 R_C)
PRODUCED BY ECM PLUS SHOT PEENING

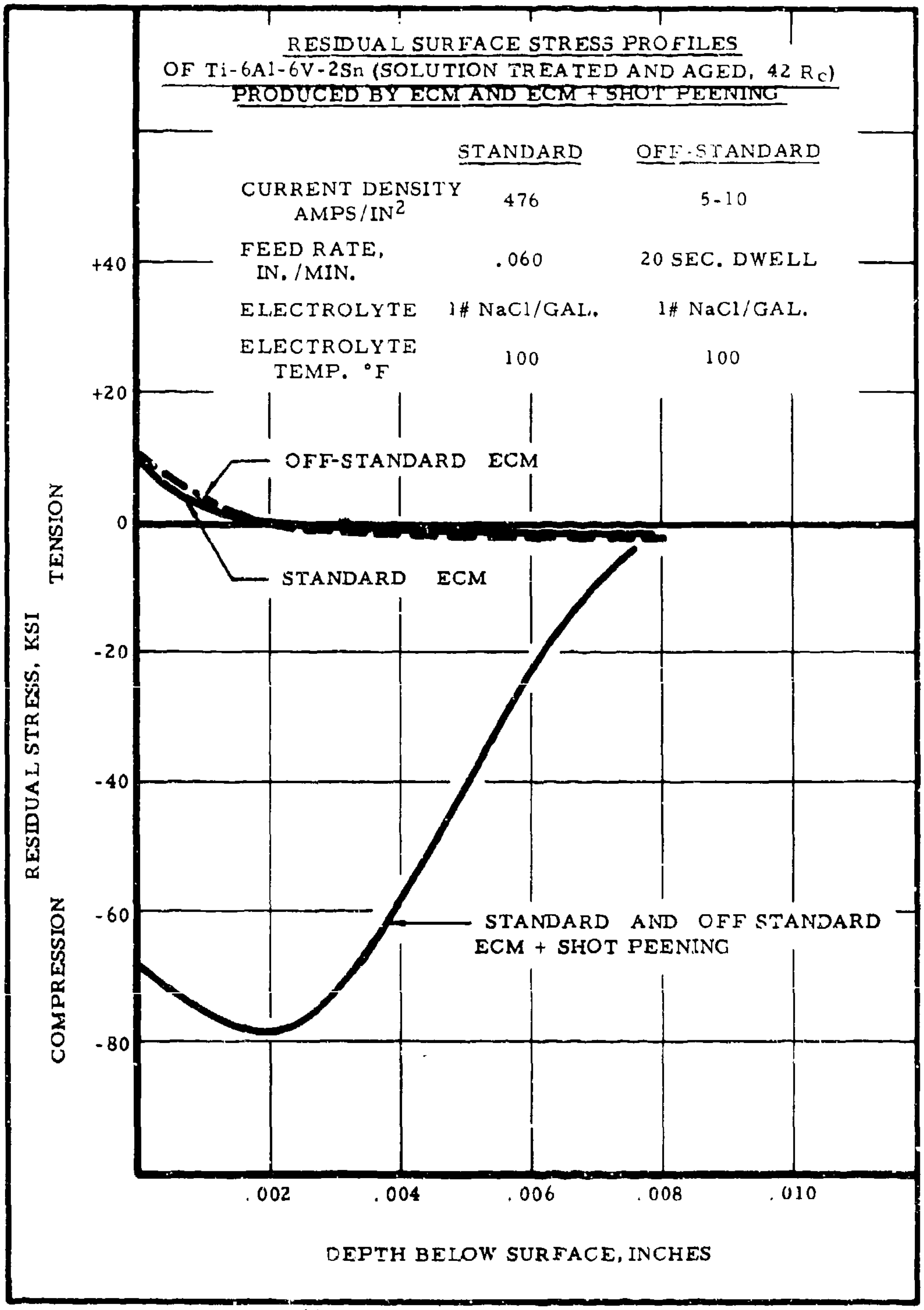


Figure 66
RESIDUAL STRESS IN TITANIUM 6Al-6V-2Sn:
ECM AND ECM + SHOT PEENING

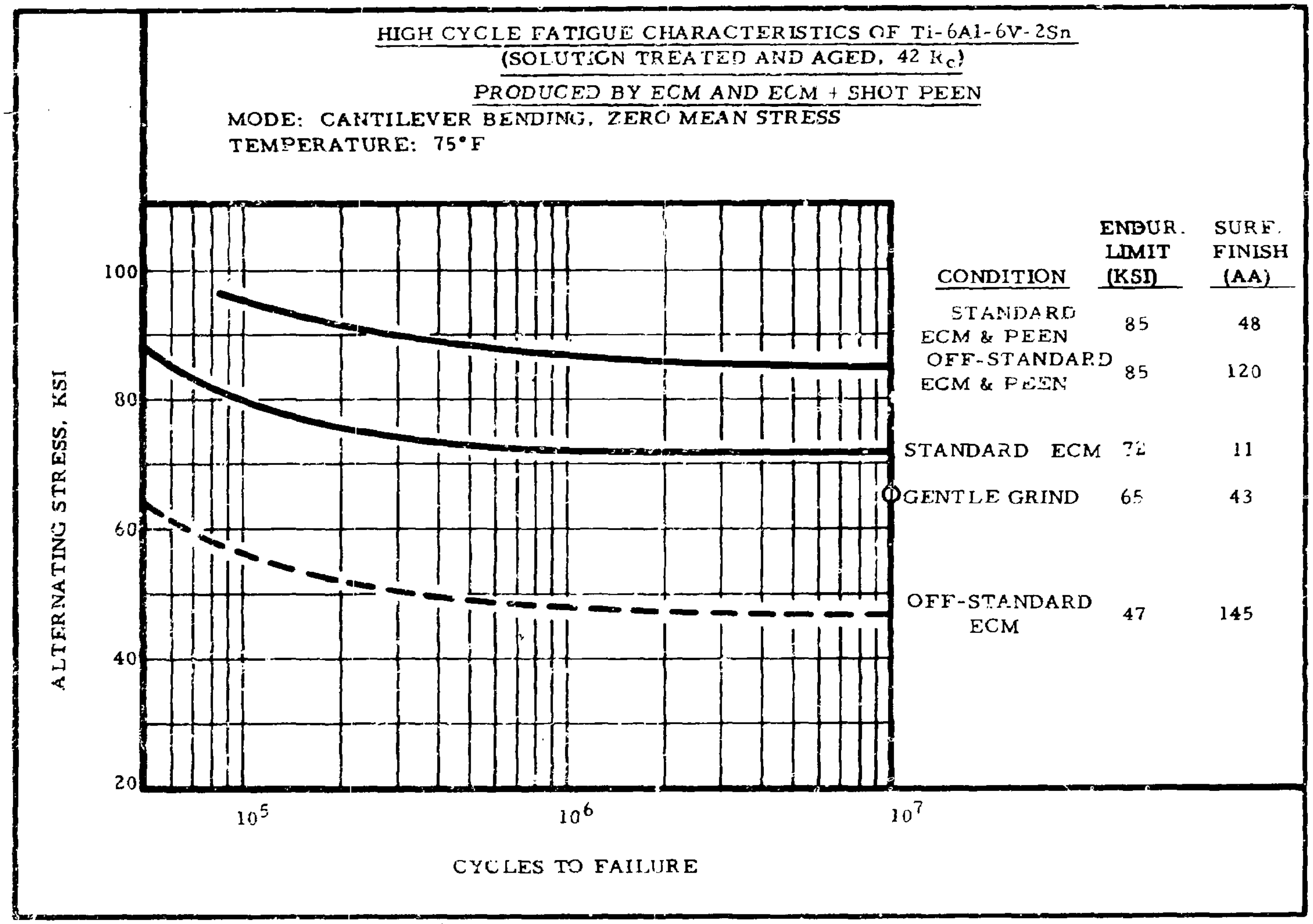


Figure 67
HIGH CYCLE FATIGUE OF TITANIUM 6Al-6V-2Sn
ECM AND ECM + SHOT PEENING

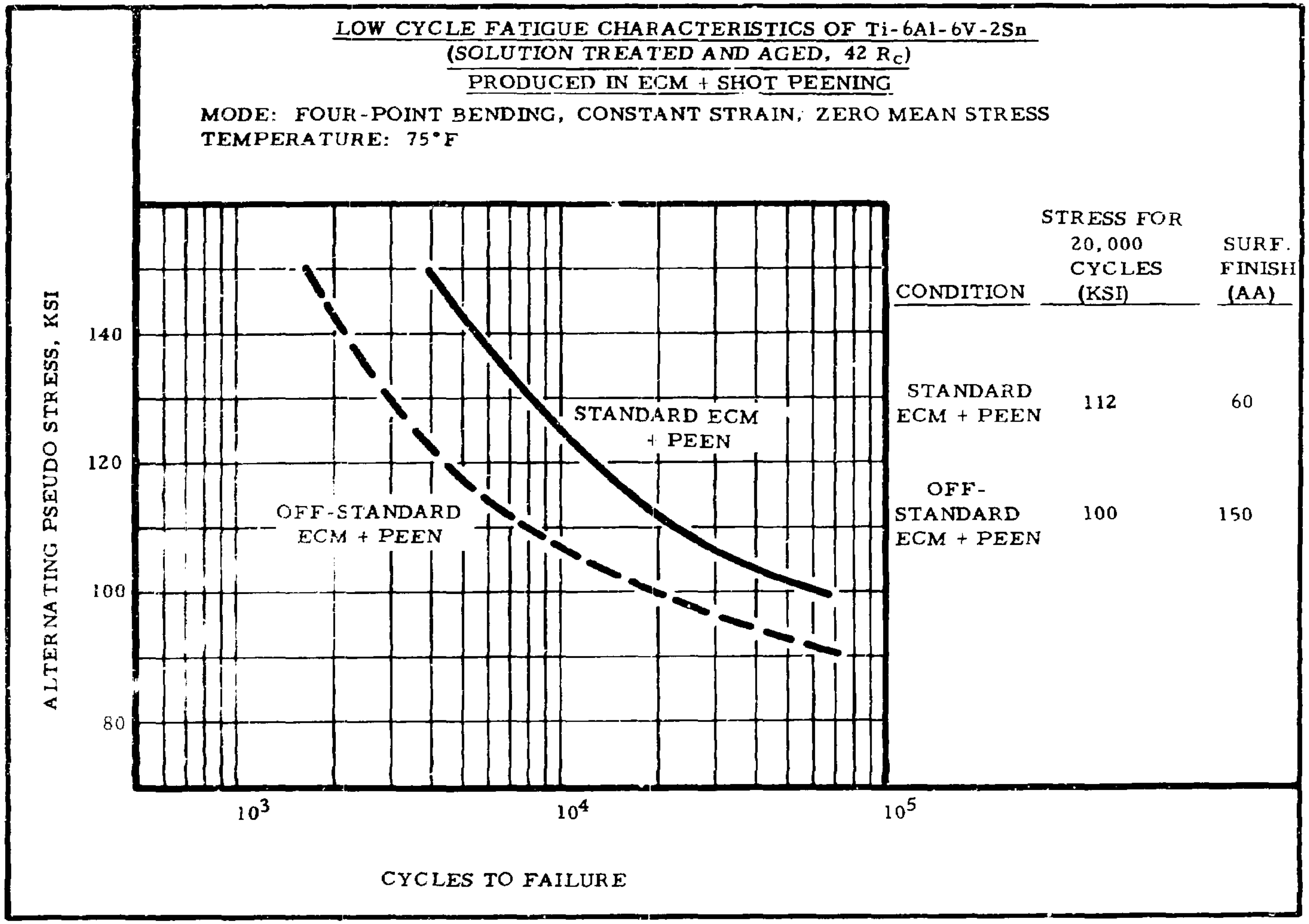


Figure 68
LOW CYCLE FATIGUE OF TITANIUM 6Al-6V-2Sn:
ECM + SHOT PEEN

6.6 Titanium 6Al-2Sn-4Zr-2Mo, Solution Treated and Aged, 36 R_c

A summary of the surface integrity behavior of this alloy as measured by high cycle fatigue strength is contained in Figure 69. Typical of titanium alloys, this material is also quite sensitive to variations in surface machining parameters. Gentle, conventional, and abusive surface grinding resulted in fatigue strengths of 68, 17, and 10 ksi, respectively. End milling-peripheral cutting also showed a marked fatigue depression when comparing gentle to abusive conditions, 82 versus 47 ksi.

Although this alloy was evaluated only in terms of surface grinding and end milling, it is probable that the sensitivities to other metal removal methods previously demonstrated for various titanium alloys would generally be found in this material.

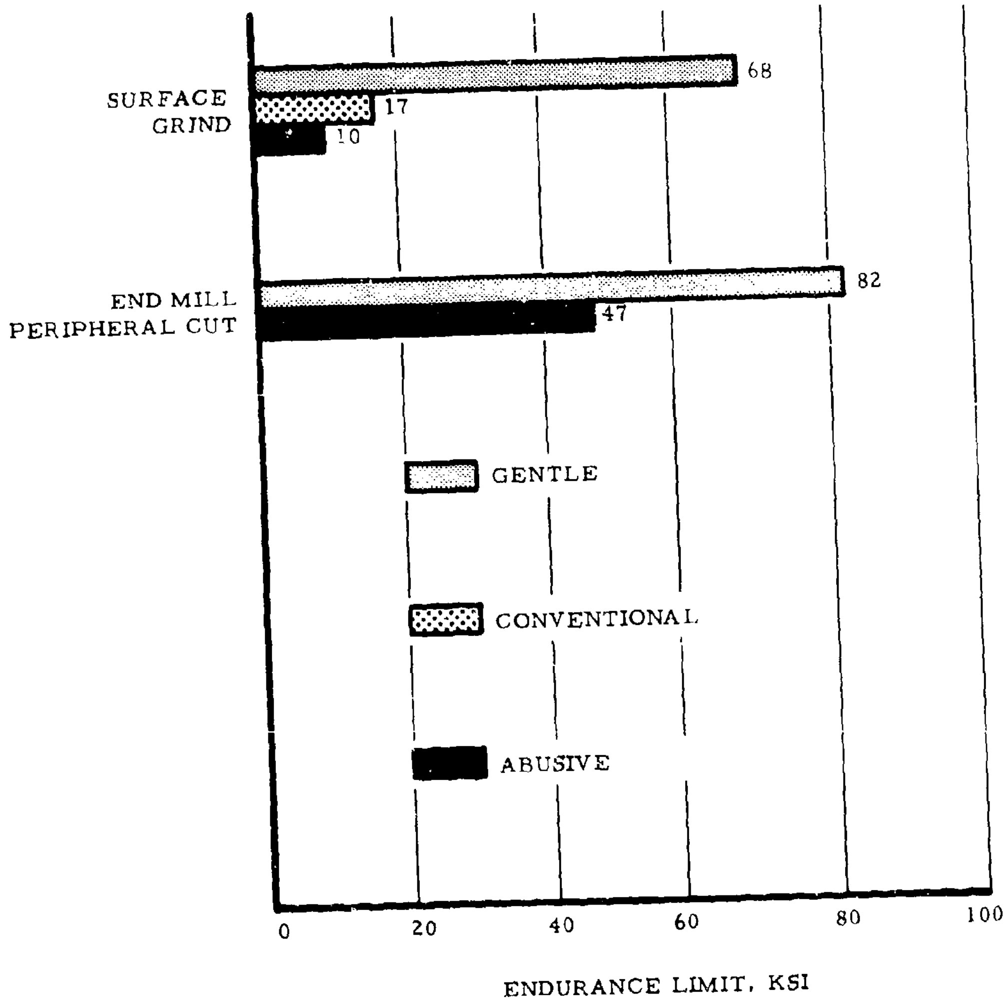


Figure 69
SUMMARY OF HIGH CYCLE FATIGUE BEHAVIOR
OF TI-6Al-2Sn-4Zr-2Mo (SOLUTION TREATED AND AGED, 36 R_c)

6.6.1 Surface Grinding - Ti-6Al-2Sn-4Zr-2Mo, STA, 36 R_C

Metallography

Photomicrographs of surface cross sections produced by gentle, conventional and abusive grinding are shown in Figure 70. The gentle surface shows a relatively smooth surface and complete freedom from plastic deformation or other types of surface alterations. The conventionally ground surface, Figure 70 (b), shows a thin plastically deformed layer, approximately .0002 in. deep. The abusively ground sample shows a much deeper layer of plastic deformation which exceeds .001 inches. None of the samples shows any microstructural effects which could be attributed to overheating. However, this material is relatively resistant to structural changes due to at least moderate heating; hence, this behavior is not particularly surprising. Microhardness measurements on all three samples show essentially no hardness change. Even in the case of the abusively ground sample, Figure 70 (c), the zone which exhibited plastic deformation yielded approximately the same microhardness measurements as the rest of the samples. This behavior is somewhat in contrast to that found in Ti-6Al-6V-2Sn, which exhibited surface softening due to grinding.

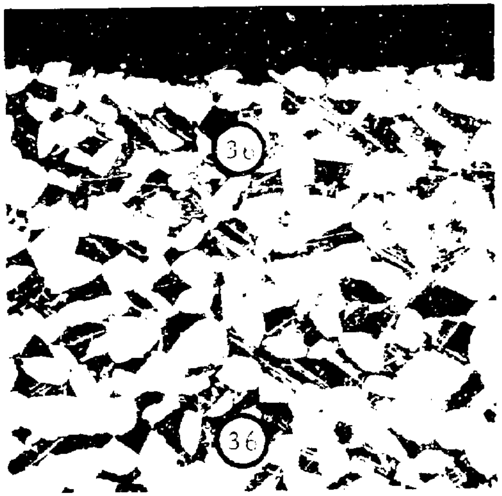
Residual Stress

Residual stress profiles produced in Ti-6Al-2Sn-4Zr-2Mo by various types of grinding are shown in Figure 71. Gentle surface grinding produced low level stresses having a peak of 10 ksi tension. Normally, gentle grinding produces compressive residual stress, but of low level. In the case of the Ti-6Al-2Sn-4Zr-2Mo, however, and also in the case of the Ti-6Al-6V-2Sn mentioned above, low level tensile stresses were produced by gentle grinding. The significant point, however, appears to be that gentle grinding does produce a relatively low residual stress profile which is normally compressive, but which may in some cases be tensile in nature. Both the conventional and abusive surface grinding resulted in fairly high residual tensile stresses having peaks in the range of 80-90 ksi. These data also shown in Figure 71 are typical of abusive grinding on a wide variety of alloys.

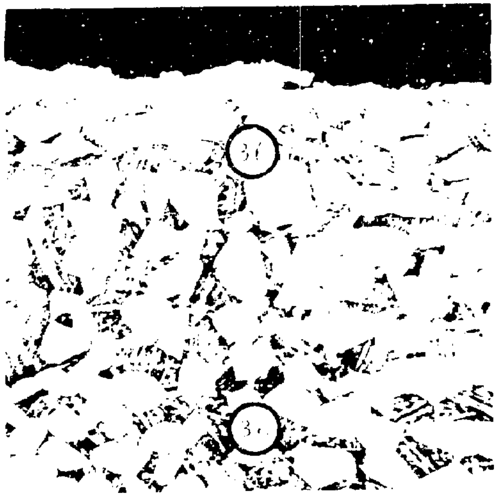
6.6.1 Surface Grinding - Ti-6Al-2Sn-4Zr-2Mo, STA, 36 R_c (continued)

High Cycle Fatigue Strength

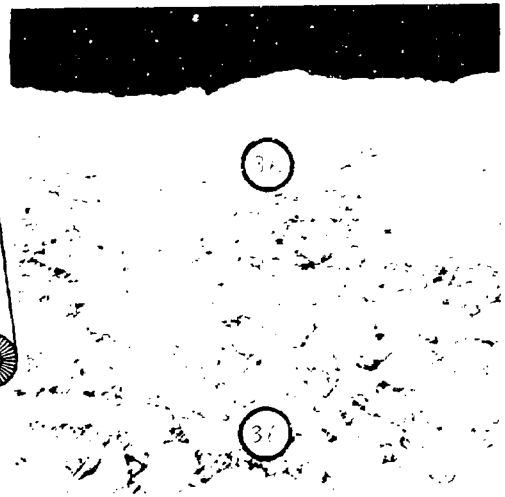
A summary of the fatigue behavior of Ti-6Al-2Sn-4Zr-2Mo due to variables in grinding is shown in Figure 72. Endurance limit associated with gentle grinding was measured as 68 ksi at 10^7 cycles. In contrast, the fatigue strengths attributable to conventional and abusive grinding were 17 and 10 ksi, respectively. These marked reductions in fatigue strength have previously been found in Ti-6Al-4V (beta rolled) and Ti-6Al-6V-2Sn, as summarized in previous reports. A complete listing of the fatigue data obtained on this alloy is contained in Table XIX.



(a) Gentle Grinding
Surface Finish:
Perpendicular to lay: 39 AA
Parallel to lay: 15 AA



(b) Conventional Grinding
Surface Finish:
Perpendicular to lay: 41 AA
Parallel to lay: 21 AA



(c) Abusive Grinding
Surface Finish:
Perpendicular to lay: 120 AA
Parallel to lay: 44 AA

Microstructures of Ti-6Al-2Sn-4Zr-2Mo show relatively low sensitivity to surface heating associated with surface grinding conditions. Abusive grinding produced a large degree of plastic deformation as may be seen in Figure 6c above. Conventional grinding (Figure 6b) also shows evidence of plastic deformation, but to a much lesser extent. Detailed microhardness data of these surfaces indicate that no significant hardness changes were present. Indicated hardness data are R_c values converted from Knoop microhardness measurements. Surface finish measurements are averages of readings made on all specimens from each group.

Magnification: 1000X

ORIENTATION: LONGITUDINAL GRIND. SURFACE SECTIONS PERPENDICULAR TO LAY.

Figure 70
SURFACE CHARACTERISTICS OF Ti-6Al-2Sn-4Zr-2Mo (SOLUTION TREATED AND AGED, 36 R_c) PRODUCED BY SURFACE GRINDING

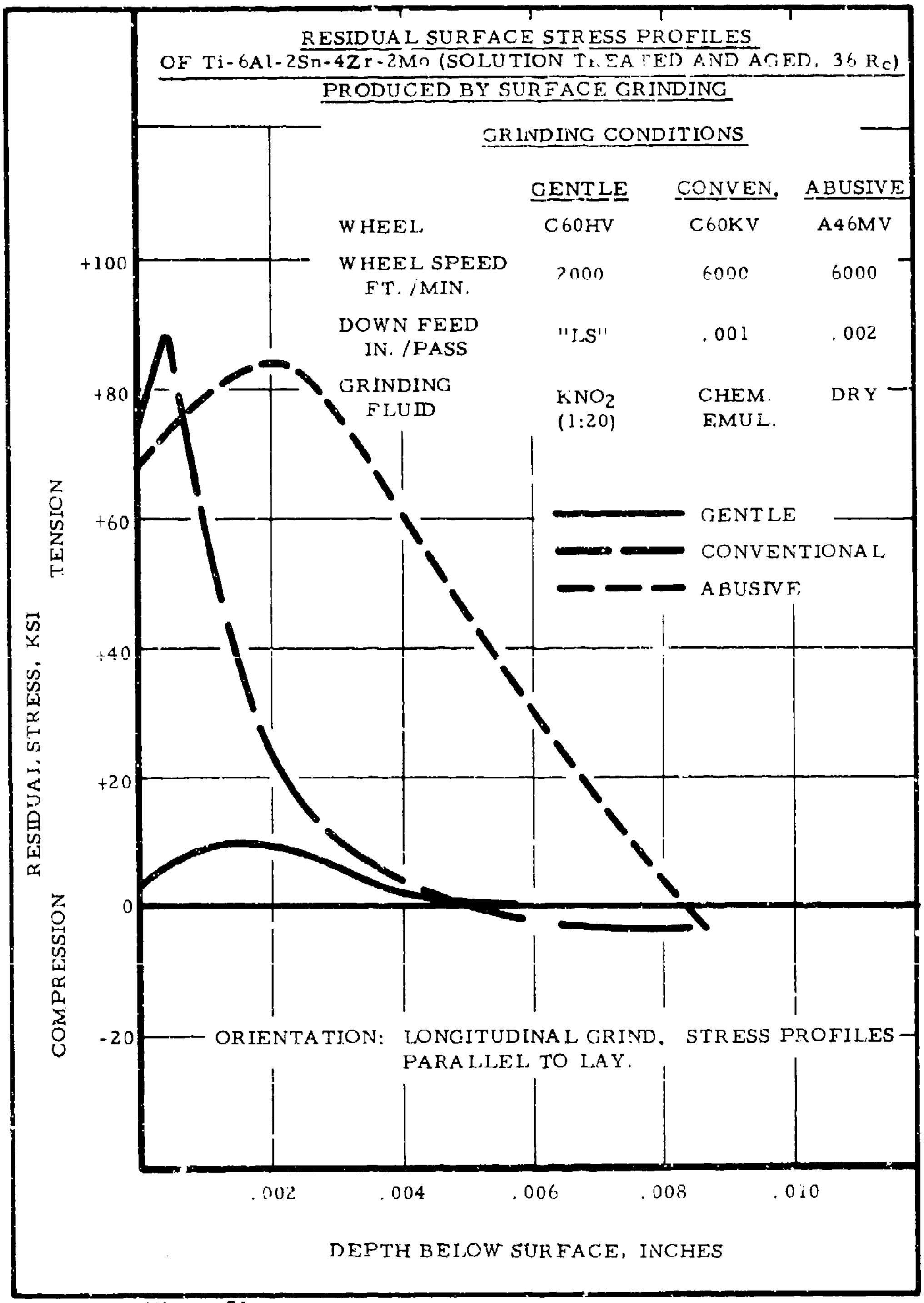


Figure 71
RESIDUAL STRESS IN TITANIUM 6Al-2Sn-4Zr-2Mo:
SURFACE GRINDING

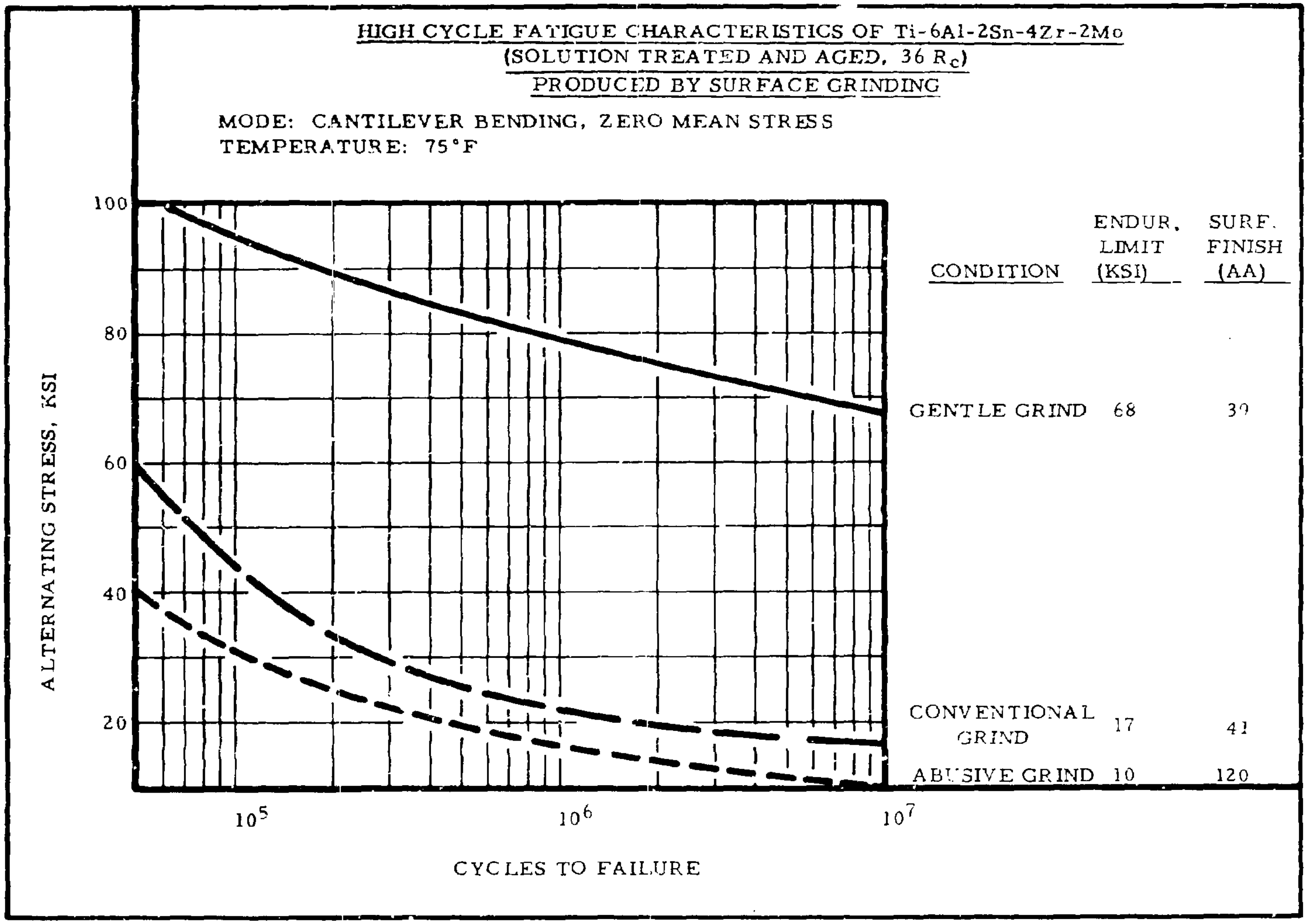


Figure 72
HIGH CYCLE FATIGUE OF TITANIUM 6Al-2Sn-4Zr-2Mo:
SURFACE GRINDING

6.6.2 End Milling-Peripheral Cutting - Ti-6Al-2Sn-4Zr-2Mo, STA 36 R_C (continued)

Metallography

Cross sections of surfaces produced by gentle and abusive end milling-peripheral cutting of Ti-6Al-2Sn-4Zr-2Mo are shown in Figure 73. A very thin layer of plastic deformation approximately .0002 in. deep may be seen on the surface of the gently milled sample (Figure 73a). A slight amount of surface softening averaging two points R_C was found to be characteristic of the gentle milling condition on this alloy.

Abusive milling produced a significant and relatively deep layer of plastically deformed or disturbed material. This is very evident and can be seen in Figure 73 (b) to be approximately .002 in. deep (2 in. in depth on the photograph which is 1000X). All of the disturbance on both of these samples appears to be primarily mechanically produced plastic deformation. No microstructural change such as darkening or resolutioning was observed, indicating a relative insensitivity of this alloy to the effects of localized surface heating. The abusively milled samples exhibited small surface hardness losses up to about three points R_C in the midst of the plastically deformed zone. This behavior indicates that the material is also not subject to strain hardening as is often associated with plastic deformation.

The milling conditions used for making the test cuts on these specimens are summarized in Table V.

Residual Stress

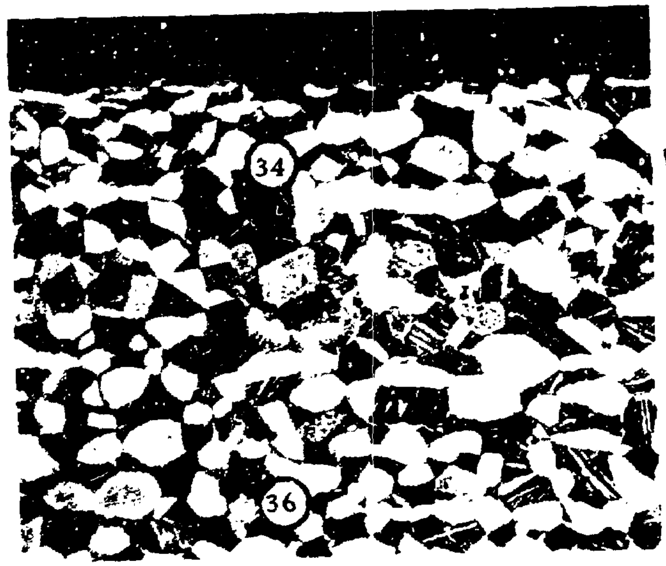
Residual stress profiles produced on this alloy as a result of both gentle and abusive peripheral end milling are shown in Figure 74. As can be seen in this figure, relatively low levels of stress were observed. Gentle milling exhibited peak stresses, separately both tensile and compressive, of less than 20 ksi. Abusive milling exhibited peak compressive stresses slightly over 30 ksi. Note, however, that the total depth to which compressive stresses were present in the abusively milled sample is considerably greater than in the gently milled sample, .010 in. versus .003 inches.

6.6.2 End Milling-Peripheral Cutting - Ti-6Al-2Sn-4Zr-2Mo, STA, 36 R_c (continued)

High Cycle Fatigue Strength

Fatigue strengths determined in this part of the test program are shown in Figure 75. Gentle milling resulted in a fatigue strength of 82 ksi. This is somewhat above the 68 ksi value determined for gentle surface grinding the same material. The abusive peripheral end milling caused a significant loss of fatigue strength, indicating an endurance limit of 10^7 cycles of 47 ksi. This behavior is generally similar to that determined for Ti-6Al-6V-2Sn reported in Section 6.5.3.

Data for the Ti-6Al-2Sn-4Zr-2Mo alloy are summarized in Table XIX.



(a) Gentle Milling
Surface Finish:
Perpendicular to lay: 36 AA
Parallel to lay: 23 AA

(b) Abusive Milling
Surface Finish:
Perpendicular to lay: 77 AA
Parallel to lay: 57 AA

A thin layer of surface alteration can be seen due to gentle milling. A very pronounced alteration approximately .002 in. deep is attributable to abusive milling. This photomicrograph (73b) shows primarily the effect of a plastically deformed surface layer. No visual effects of localized surface heating such as darkening or resolutioning are evident due to the thermal resistance of the alloy. Small drops in hardness as indicated on the photomicrographs were observed in the surface regions. Indicated hardness data are R_c values converted from Knoop microhardness measurements. Surface finish measurements are averages of readings made on all specimens from each group.

Magnification: 1000X

ORIENTATION: LONGITUDINAL MILL. SURFACE SECTIONS PERPENDICULAR TO LAY.

Figure 73
SURFACE CHARACTERISTICS OF Ti-6Al-2Sn-4Zr-2Mo (SOLUTION TREATED AND AGED, 36 R_c) PRODUCED BY END MILLING - PERIPHERAL CUTTING

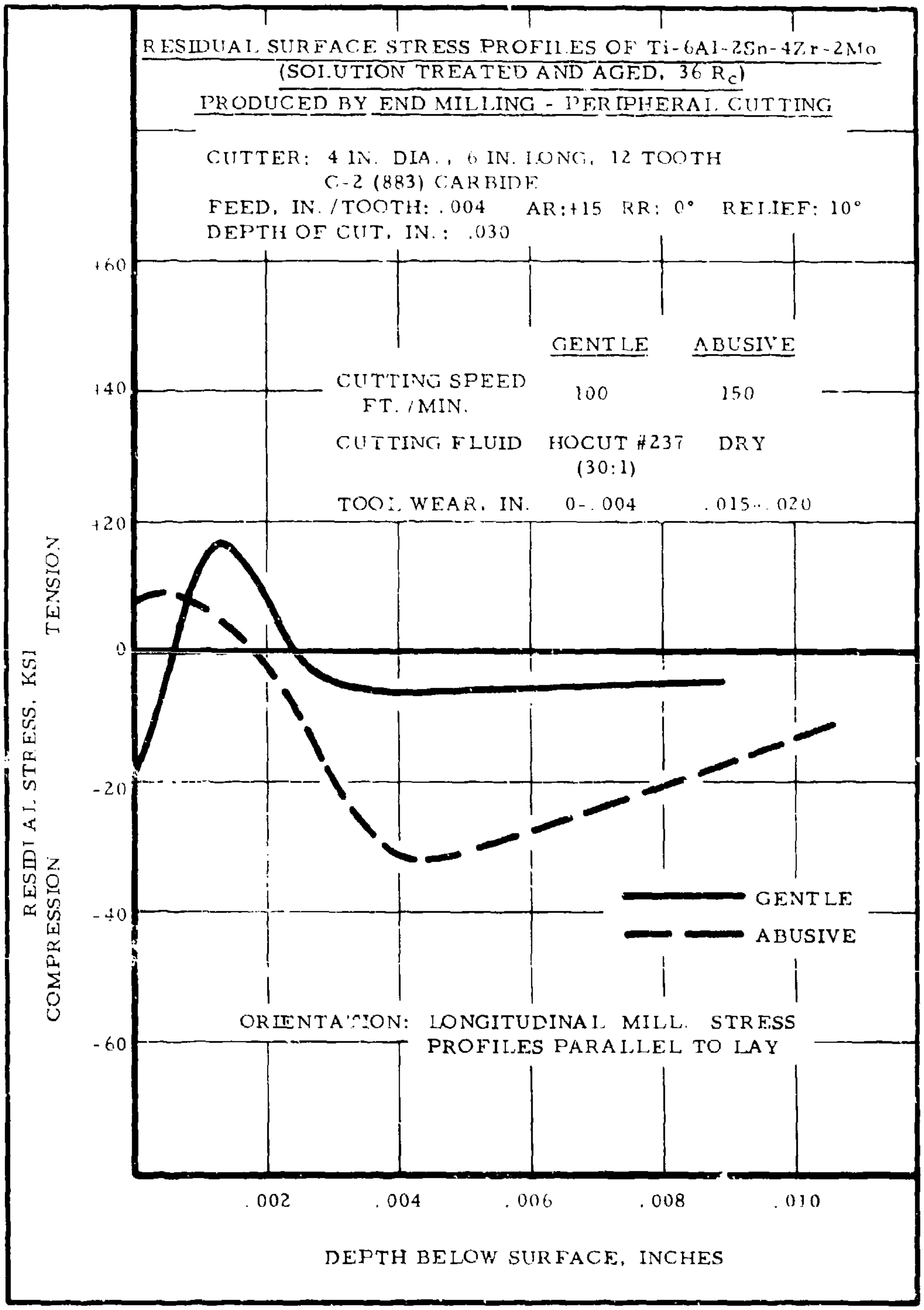


Figure 74
RESIDUAL STRESS IN TITANIUM 6Al-2Sn-4Zr-2Mo;
END MILLING - PERIPHERAL CUTTING

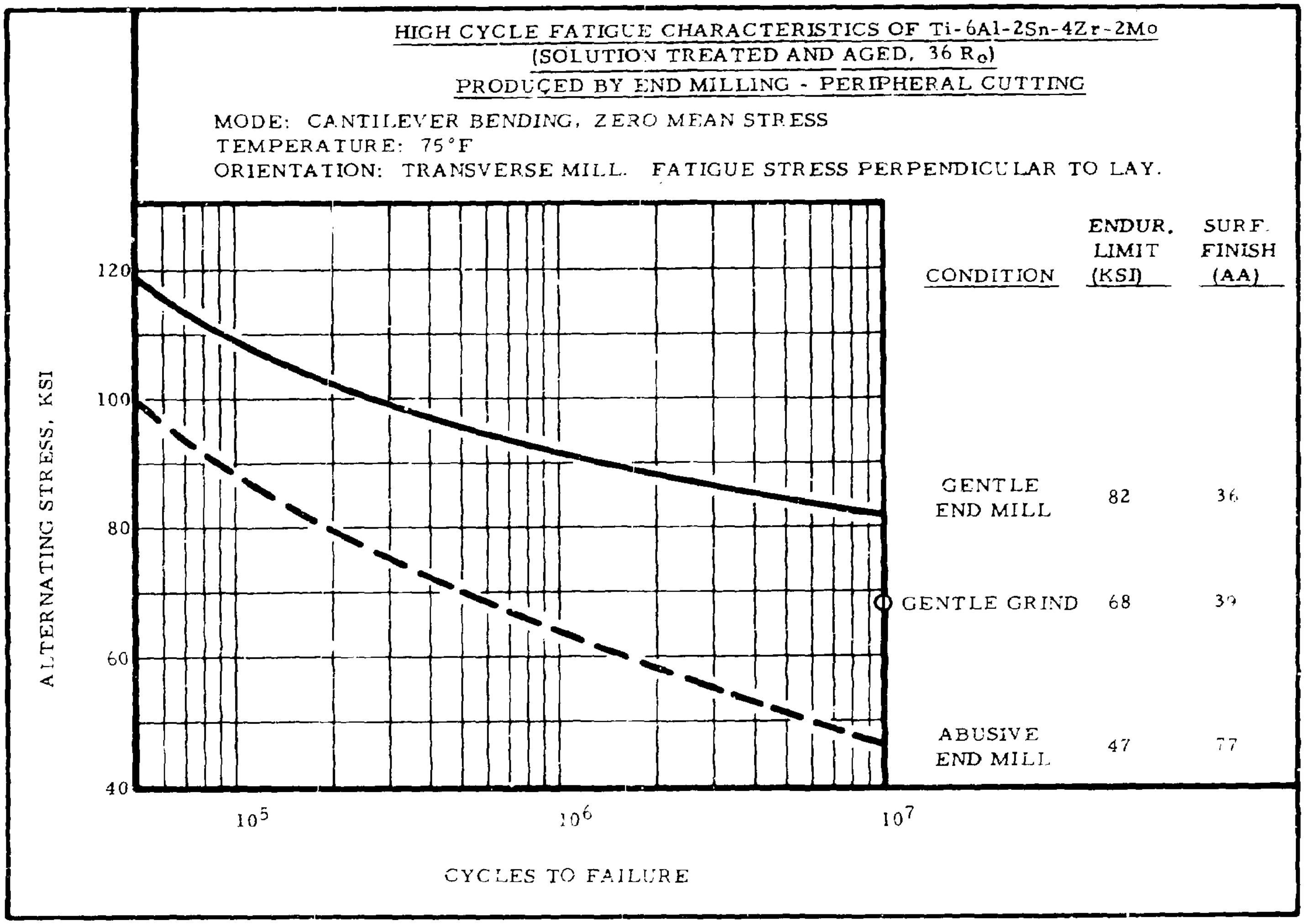


Figure 75
HIGH CYCLE FATIGUE OF TITANIUM 6Al-2Sn-4Zr-2Mo:
END MILLING - PERIPHERAL CUTTING

6.7 Inconel 718, Solution Treated and Aged, 44 R_c

A summary of the surface integrity behavior of this alloy as indicated by high cycle and low cycle fatigue strengths is shown in Figures 76 and 77. Inconel 718 shows a significant sensitivity to surface grinding variables. As indicated in Figure 76, shifting from gentle to conventional grinding caused a fatigue depression of from 60 to 24 ksi. Variations in turning (facing), ECM, and EDM, however, did not cause differences in fatigue behavior indicating that Inconel 718 is insensitive to variations in these processes within the ranges studied. Note, however, that EDM and ECM exhibited basic endurance limits considerably below those associated with gentle grinding. EDM, in fact, yields a fatigue strength lower than that produced by conventional grinding, 22 versus 24 ksi.

It may also be seen in Figure 76 that peening when applied to variously produced surfaces as a post treatment is effective in significantly raising the fatigue strength of the material. In all cases where peening was applied to Inconel 718, the high cycle fatigue strength was raised to a level which exceeded that exhibited by the gentle grinding.

Low cycle fatigue behavior, measured in terms of the stress to produce a life of 20,000 cycles, shows the same relative behavior as exhibited by high cycle fatigue strength. As indicated in Figure 77, low cycle fatigue strength at 20,000 cycles due to gentle versus abusive grinding was measured as 160 versus 127 ksi. Low cycle fatigue strength for turned surfaces was the same as a result of both gentle and abusive conditions; however, high cycle fatigue behavior also gave equal values for gentle and abusive turning conditions. Equivalent behavior is also shown for ECM plus peening.

In still another study, an indication was obtained regarding the translatability of surface integrity behavior to an elevated temperature situation. As was indicated in Figure 77, comparative elevated temperature behavior for turning and ECM plus peening were in proportion to the corresponding behavior at room temperature.

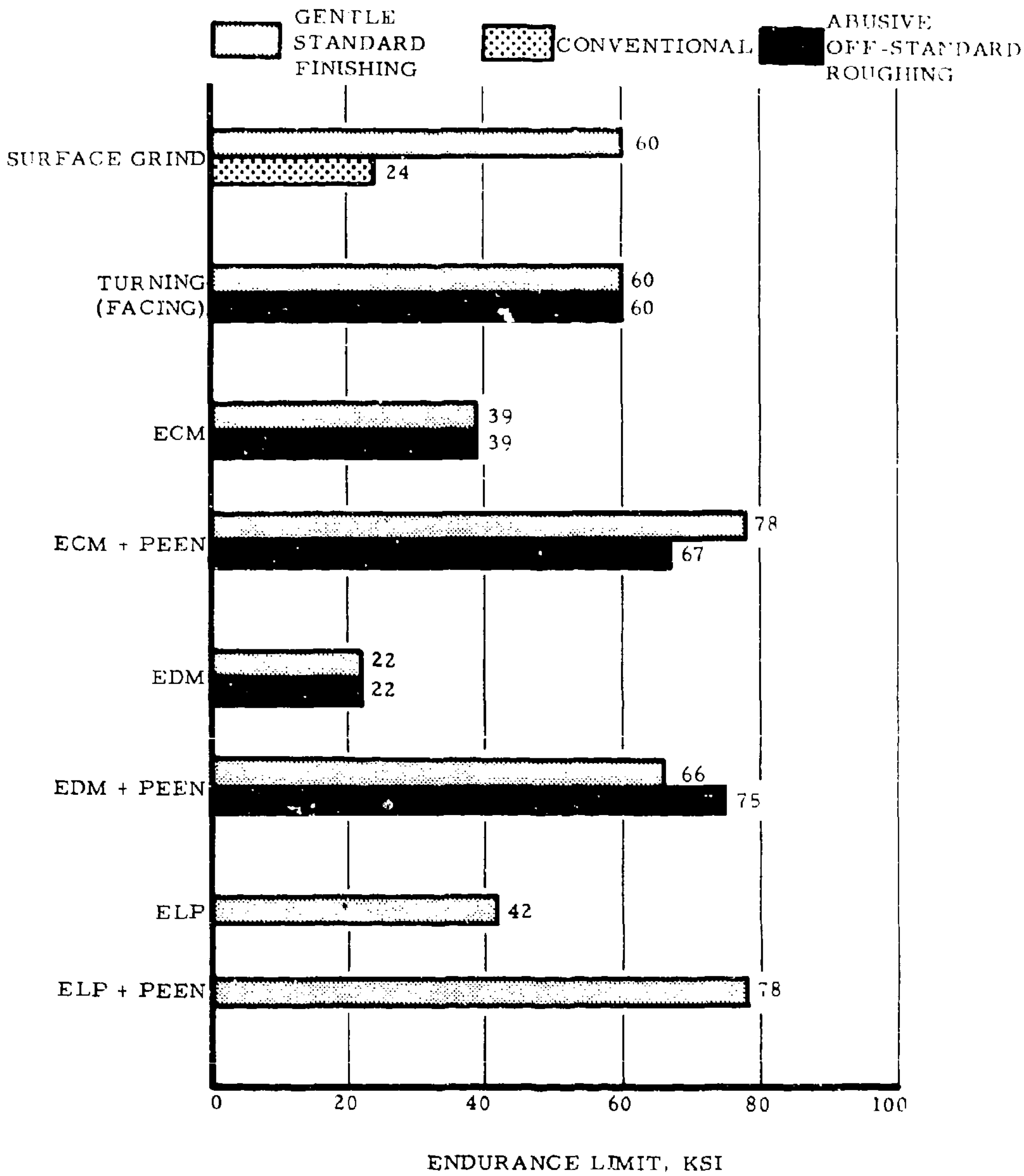


Figure 76
SUMMARY OF HIGH CYCLE FATIGUE BEHAVIOR OF INCONEL 718 (SOLUTION TREATED AND AGED, 44 R_c)

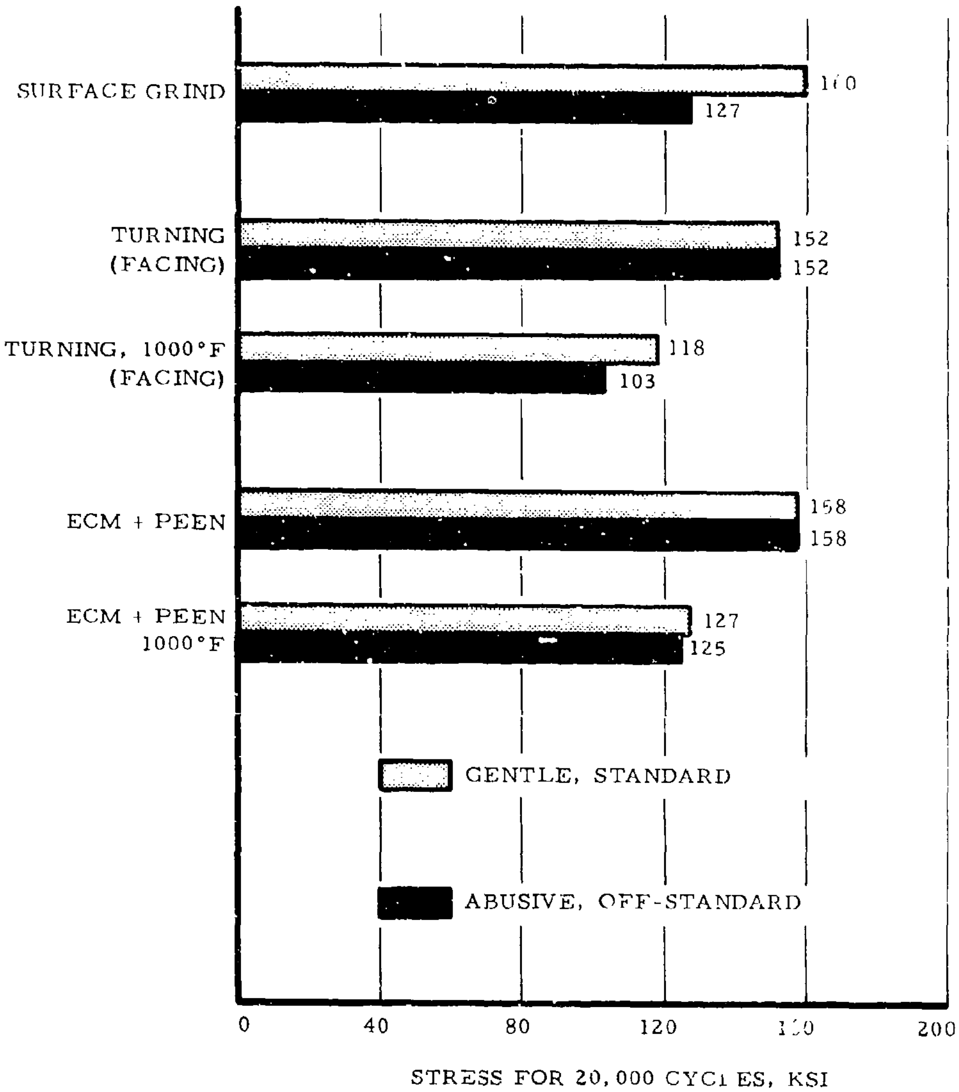


Figure 77
SUMMARY OF LOW CYCLE FATIGUE BEHAVIOR
OF INCONEL 718, SOLUTION TREATED AND AGED (44 R_c)

6.7.1 Surface Grinding - Inconel 718, STA, 44 R_c

Metallography

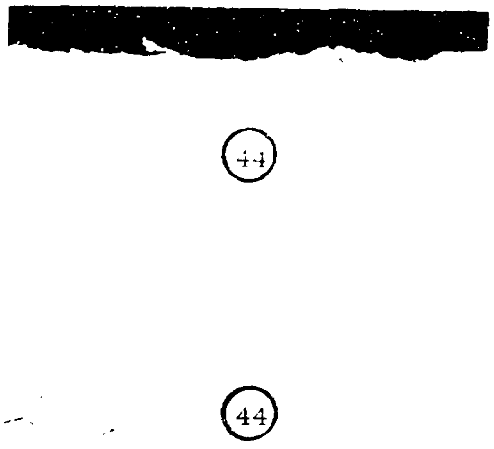
To provide metallographic reference for the presentation of low cycle fatigue data, a metallographic summary of Inconel 718 behavior associated with surface grinding has been extracted from previous work and is shown in Figure 78. As can be seen, this alloy does not exhibit any effects due to localized surface heating associated with grinding. Likewise, there is no significant indication of surface damage or alterations in the structure. Microhardness studies confirm the lack of any detectable effects since no microhardness loss at the surface was evident.

Residual Stress

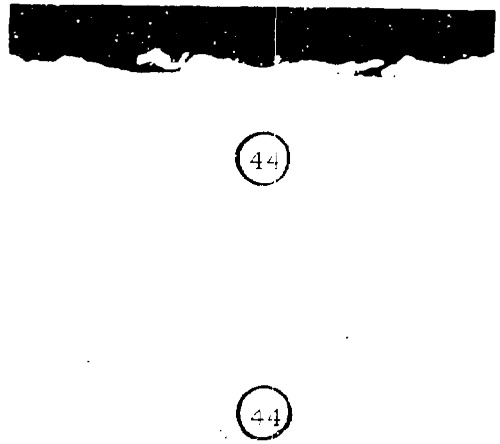
Residual stress distribution measured in Inconel 718 as a result of surface grinding variables is shown in Figure 79. Notice that gentle grinding produces the typical compressive stress near the surface of relatively low value, in this case, approaching 40 ksi. In contrast, both conventional and abusive grinding produces relatively high tensile stresses of approximately 130 ksi. The total stress layer is considerably deeper, in the range of .010" as compared to .003" for the gentle grinding condition.

Low Cycle Fatigue Strength

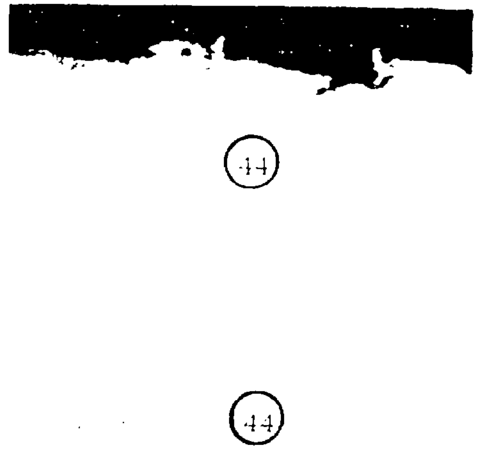
A summary of low cycle fatigue characteristics of Inconel 718 associated with surface grinding is shown in Figure 80. Detailed test data are included in this report as Table XXI. At the 160 ksi stress level, specimen life dropped from 20,000 to 9,200 cycles by shifting from gentle to abusive grinding. The stress required to achieve a 20,000 cycle life similarly dropped from 160 to 127 ksi. While the adverse effect of abusive grinding is unquestionably present, the magnitude of the effect is somewhat less than had been previously determined in high cycle fatigue testing. In this particular instance, however, the detrimental effects of abusive grinding are sufficient to be a cause for concern should components of Inconel 718 be operating under conditions which makes their life limit be their low cycle fatigue behavior.



(a) Gentle Grinding
Surface Finish:
Perpendicular to lay: 13 AA
Parallel to lay:



(b) Conventional Grinding
Surface Finish:
Perpendicular to lay: 41 AA
Parallel to lay:



(c) Abusive Grinding
Surface Finish:
Perpendicular to lay: 70 AA
Parallel to lay:

The response of Inconel 718 to surface grinding shows little or no sensitivity to localized heating as indicated in the above photomicrographs. Abusive conditions cause a surface which appears to be *somewhat rougher on a microscale and is, in fact, rougher* as measured by the electronic instrumentation used to determine surface finish values. No microhardness changes within .001 in. of the surface were detected on any of the samples, as indicated above. Likewise, no plastic deformation is evident. Indicated hardness data are R_C values converted from Knoop microhardness measurements. Surface finish measurements are averages of readings made on all specimens from each group.

Magnification: 1000X

ORIENTATION: LONGITUDINAL GRIND SURFACE SECTIONS PERPENDICULAR TO GRINDING LAY

Figure 78
SURFACE CHARACTERISTICS OF INCONEL 718 (SOLUTION TREATED AND AGED, 44 R_C) PRODUCED BY SURFACE GRINDING

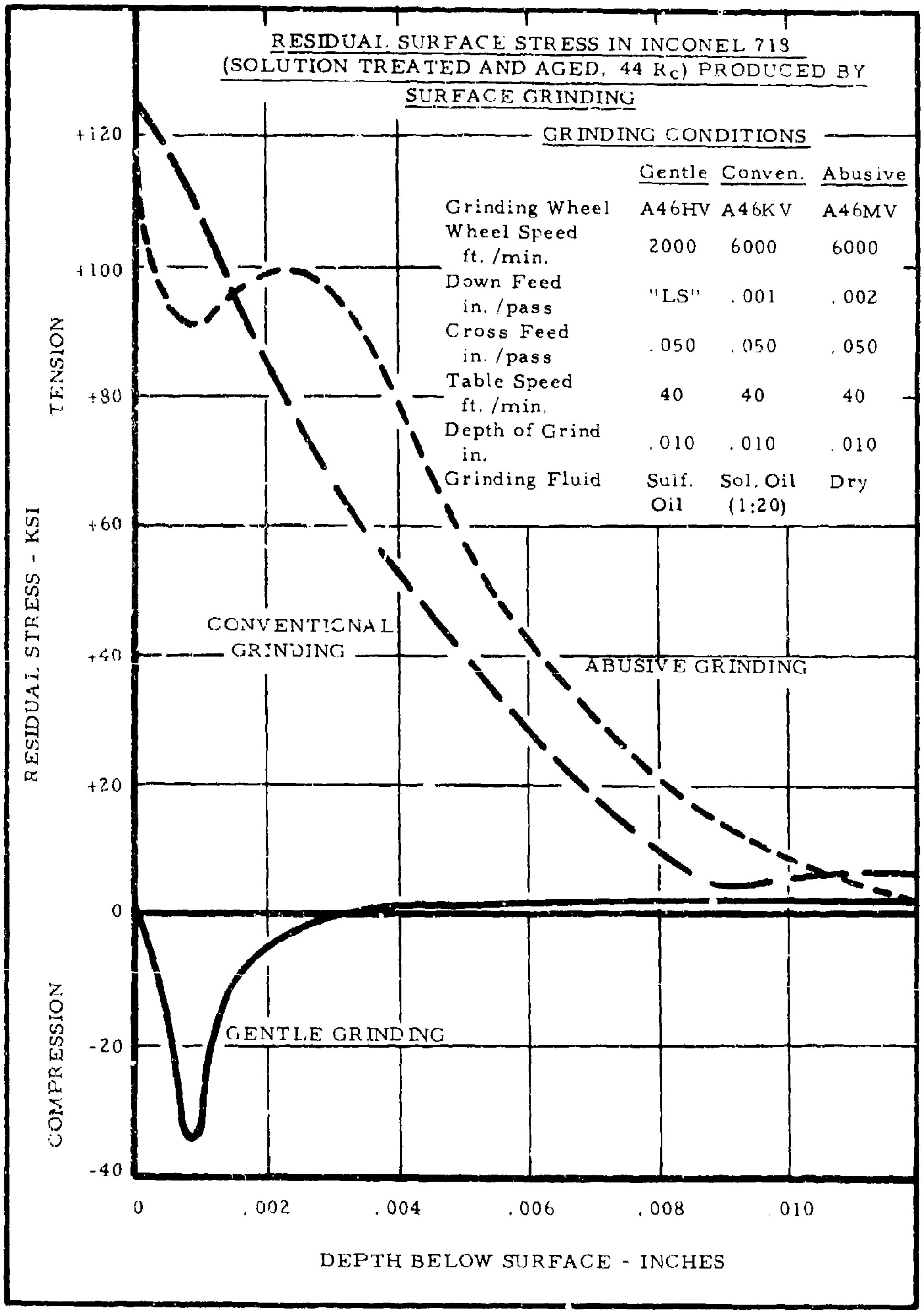


Figure 79
RESIDUAL STRESS IN INCONEL 718:
SURFACE GRINDING

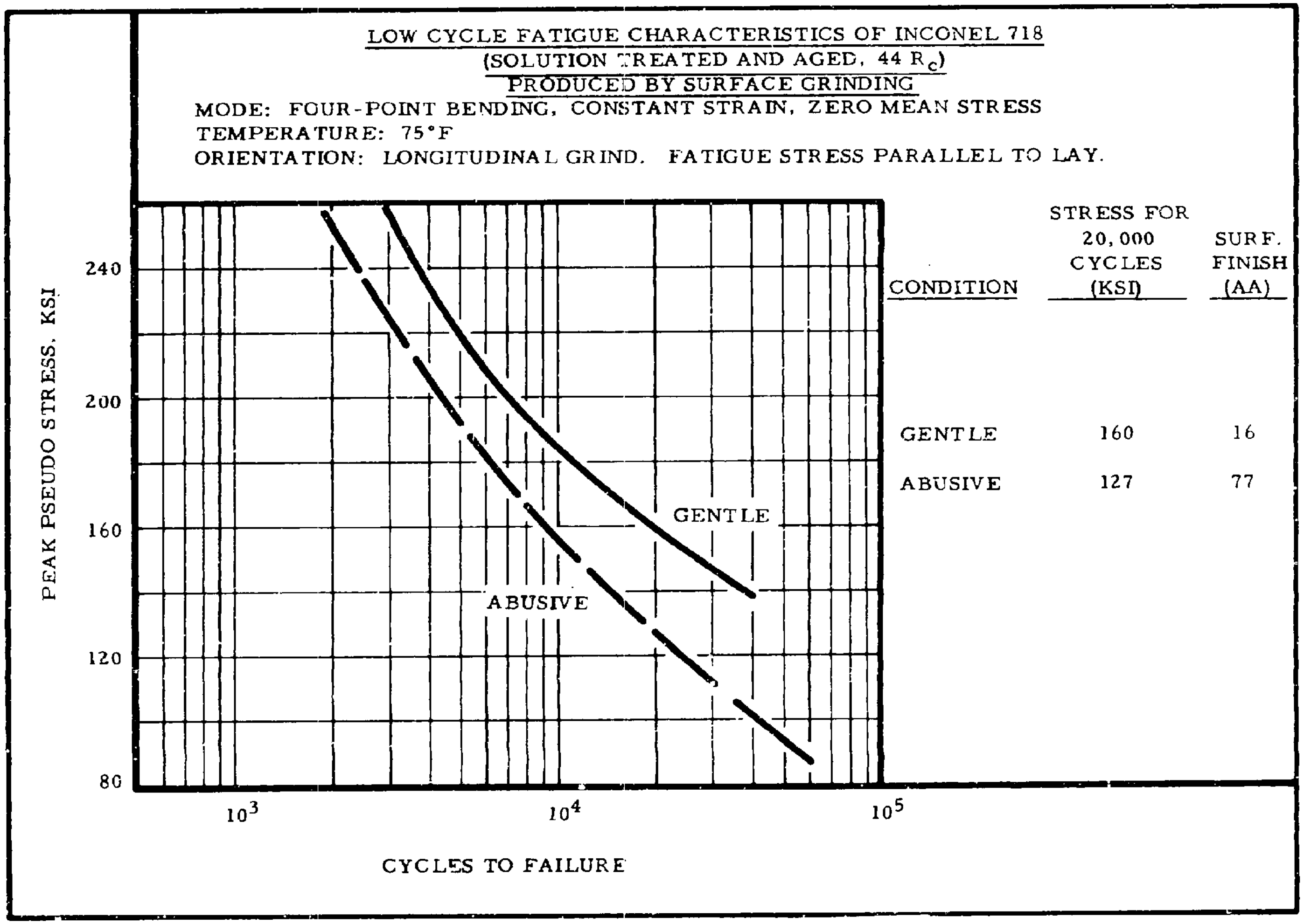


Figure 80
LOW CYCLE FATIGUE OF INCONEL 718:
SURFACE GRINDING

6.7.2 Turning - Inconel 718, STA, 44 R_c

Inconel 718 was subjected to a detailed study exploring the effects of surface finish variations on surface integrity behavior under both gentle and abusive turning conditions. A complete summary of the metallography, residual stress and high cycle fatigue behavior of the alloy is included as Section 6.11.3 of this report.

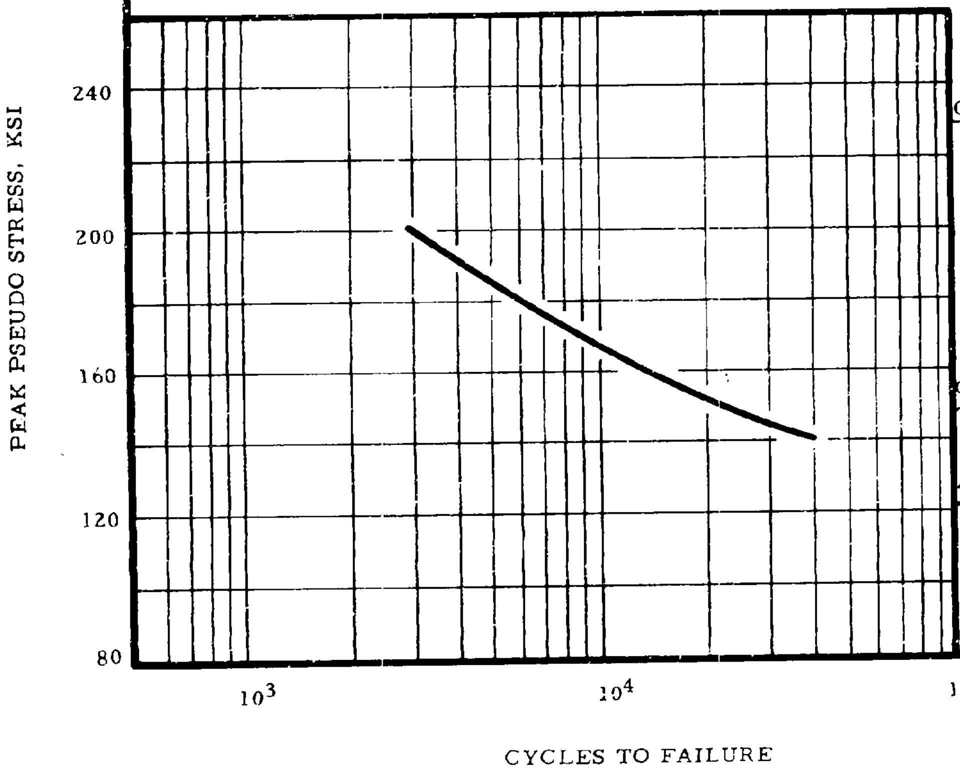
Low Cycle Fatigue Strength

In low cycle fatigue testing at room temperature, turned surfaces of Inconel 718 exhibited no difference in fatigue behavior as a result of gentle versus abusive conditions. All of the tests run for these conditions, as summarized in Table XXI, fell on a single curve, shown in Figure 81. This displays essentially the same behavior as was indicated in the high cycle fatigue tests of this alloy in the turned condition. The low cycle fatigue behavior of this alloy at a simulated service temperature of 1000°F shows a slight separation due to gentle versus abusive grinding. At the 20,000 cycle level, the data indicates a loss in strength capability of from 118 to 103 ksi due to a shift from gentle to abusive turning. This is shown in Figure 82.

LOW CYCLE FATIGUE CHARACTERISTICS OF INCONEL 718 (SOL. TREATED AND AGED, 44 R_c)

PRODUCED BY TURNING (FACING)

MODE: FOUR POINT BENDING, CONSTANT STRAIN, ZERO MEAN STRESS
TEMPERATURE: 75°F
ORIENTATION: TRANSVERSE TURN. FATIGUE STRESS PERPENDICULAR TO LAY.



CONDITION	STRESS FOR 20,000 CYCLES (KSI)	SURF. FINISH (AA)
GENTLE TURN	152	77
ABUSIVE TURN	152	70

Figure 81
LOW CYCLE FATIGUE OF INCONEL 718:
TURNING (FACING)

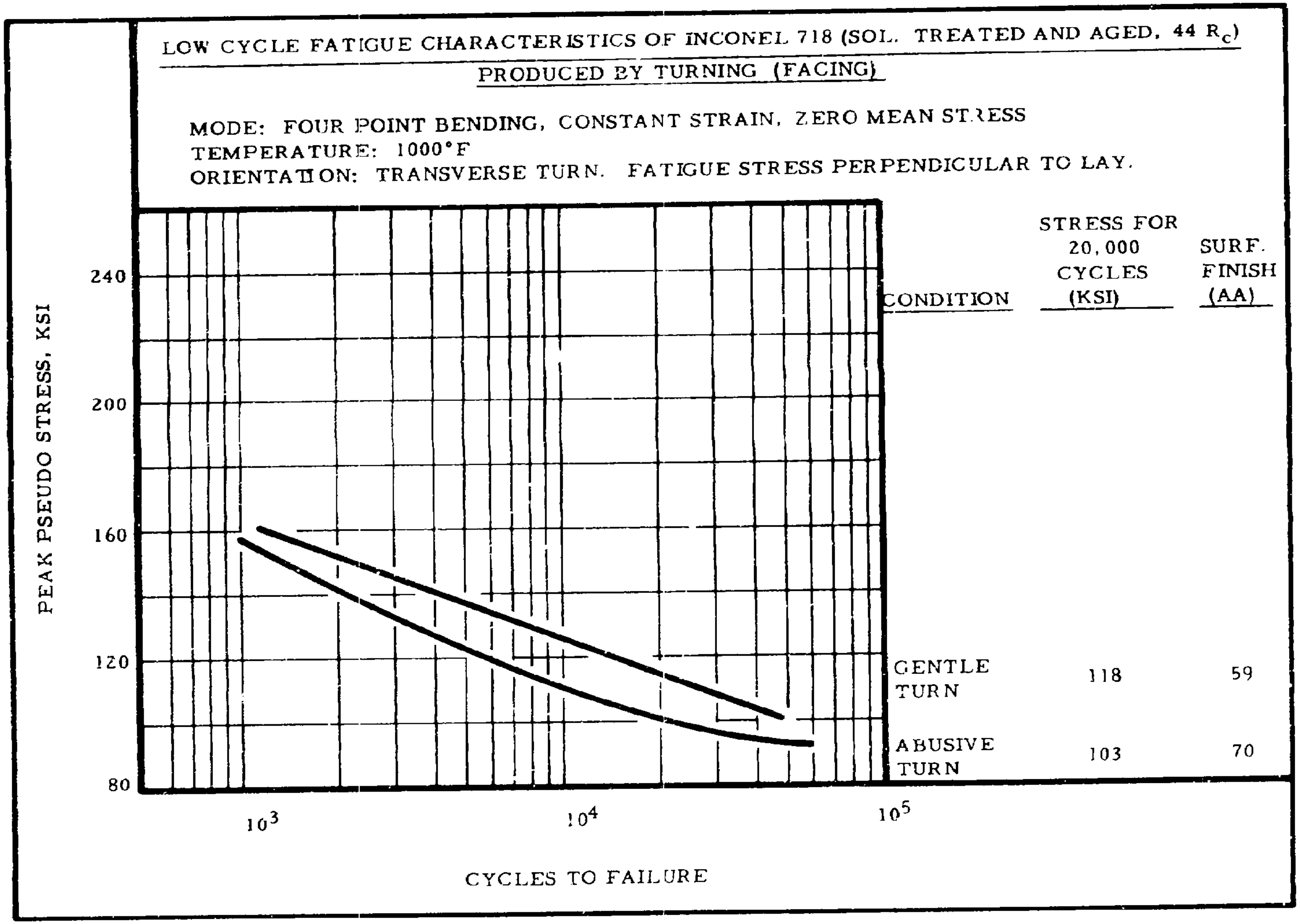


Figure 82
LOW CYCLE FATIGUE OF INCONEL 718:
TURNING (FACING)

6.7.3 ECM Plus Peening - Inconel 718, STA, 44 R_c

A surface integrity evaluation of ECM applied to Inconel 718 has been previously reported in AFML-TR-70-11. This data is summarized in Figure 76. A low cycle fatigue evaluation of the ECM plus peen condition was run under the present contract. Background data on the metallography and residual stress characteristics of this alloy/metal removal combination are included here for reference.

Metallography

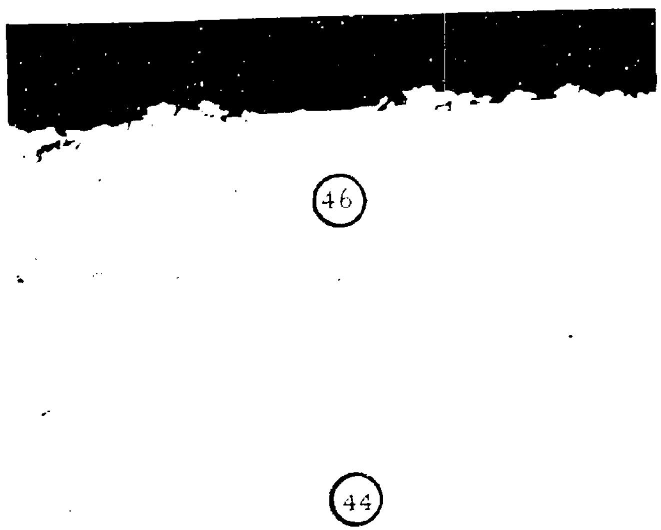
Photomicrographs illustrating sections of surfaces which have been ECM'd and then peened are shown in Figure 83. Peening conditions are indicated in Table XI. Notice the roughness of the surface and also the surface cracking evidenced in Figure 83 (b). As indicated in this figure, a slight microhardness increase of 2 to 3 points R_c shows evidence in the first .002" beneath the surface. This is perhaps due to deformation resulting from peening. Neither of these surfaces show any evidence of surface alteration resulting from the ECM operation. The cracking which may be seen in Figure 83 (b) is the result of peening. Shallow surface cracking is occasionally found as a result of peening action on nickel alloys.

Residual Stress

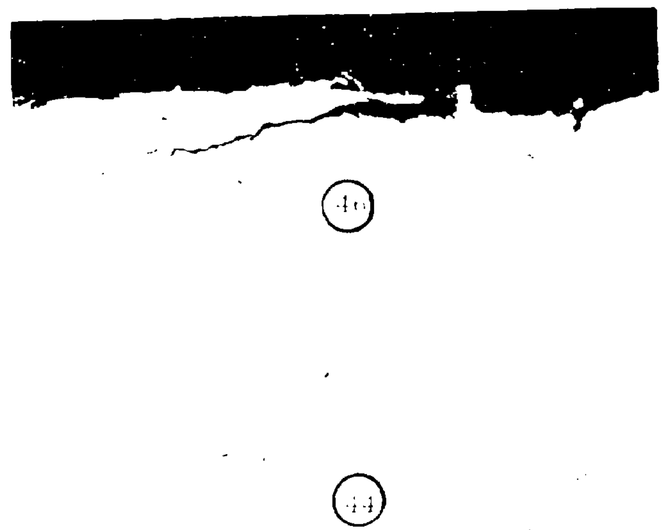
Residual stress behavior of Inconel 718 which has been finished by ECM and subsequently peened is shown in Figure 84. Note the high surface compression in these samples which is characteristic of shot peening.

Low Cycle Fatigue Strength

A summary of the room temperature low cycle fatigue behavior of Inconel 718 as the result of ECM plus peening is shown in Figure 85. The corresponding behavior at 1000°F is shown in Figure 86. As can be seen in both of these illustrations, the fatigue response of this alloy is insensitive to processing parameters. The low cycle fatigue strength at 1000°F is approximately 20 percent lower than at room temperature. This, however, is normal behavior for the material. Individual test data are summarized in Table XXI.



(a) Standard Conditions
Surface Finish: 53 AA



(b) Off-Standard Conditions
Surface Finish: 56 AA

The cross sections of surfaces above show the effect of ECM + shot peening typically found on nickel alloys. Notice the unevenness of the surface and also the cracking evidenced in Figure (b). The cracking effect is probably due to peening action rather than the off-standard ECM. A slight increase in microhardness as indicated was found in the first .002 in. beneath the surface. This probably associated with plastic deformation due to peening. Indicated hardness data are R_c values converted from Knoop microhardness measurements. Surface finish measurements are averages of readings made on all specimens from each group.

Magnification: 1000X

Figure 83
SURFACE CHARACTERISTICS OF INCONEL 718 (SOLUTION TREATED AND AGED. 44 R_c)
PRODUCED BY ECM PLUS SHOT PEENING

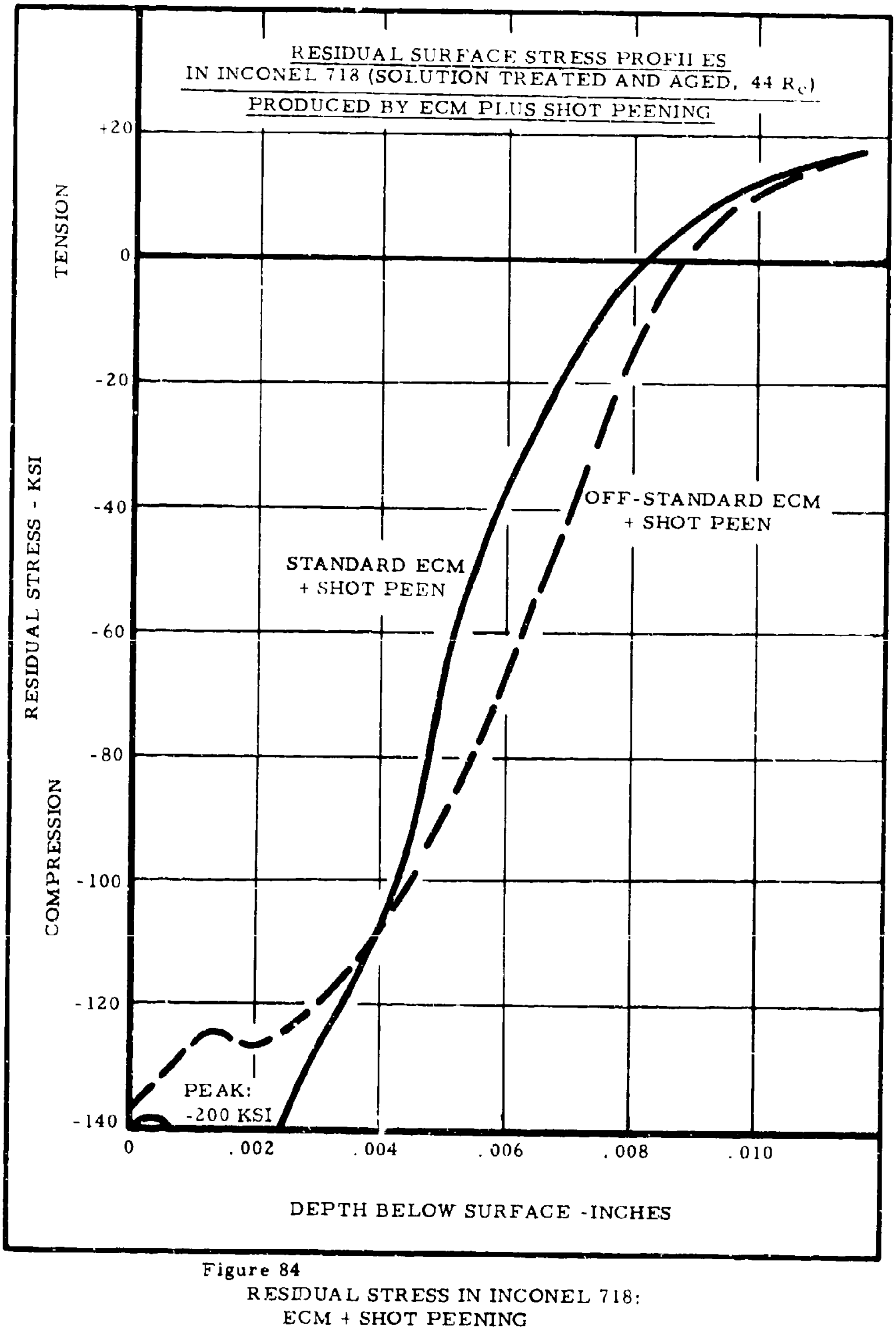
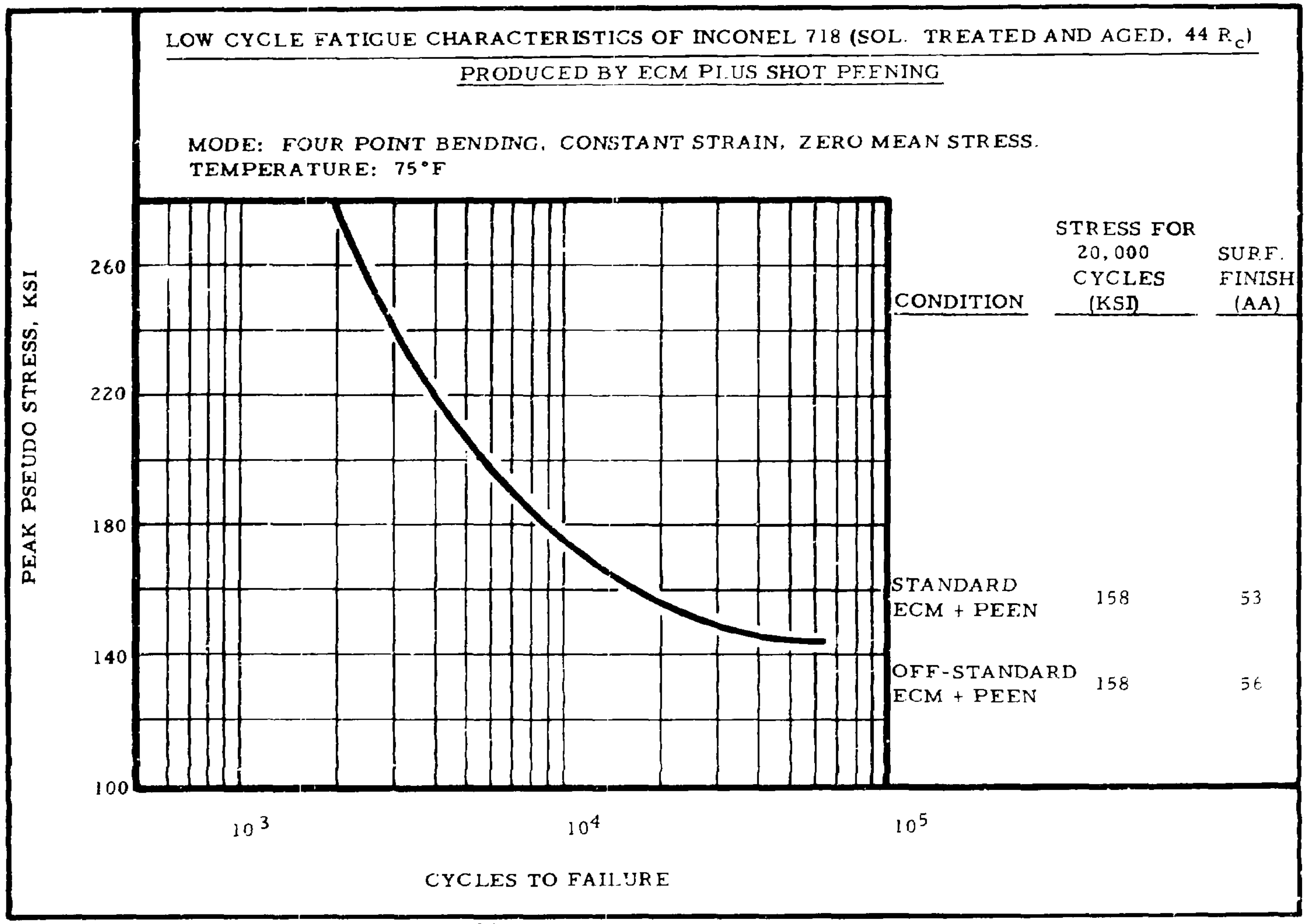


Figure 84
RESIDUAL STRESS IN INCONEL 718:
ECM + SHOT PEENING



CONDITION	STRESS FOR 20,000 CYCLES (KSI)	SURF. FINISH (AA)
STANDARD ECM + PEEN	158	53
OFF-STANDARD ECM + PEEN	158	56

Figure 85
LOW CYCLE FATIGUE OF INCONEL 718:
ECM - SHOT PEENING

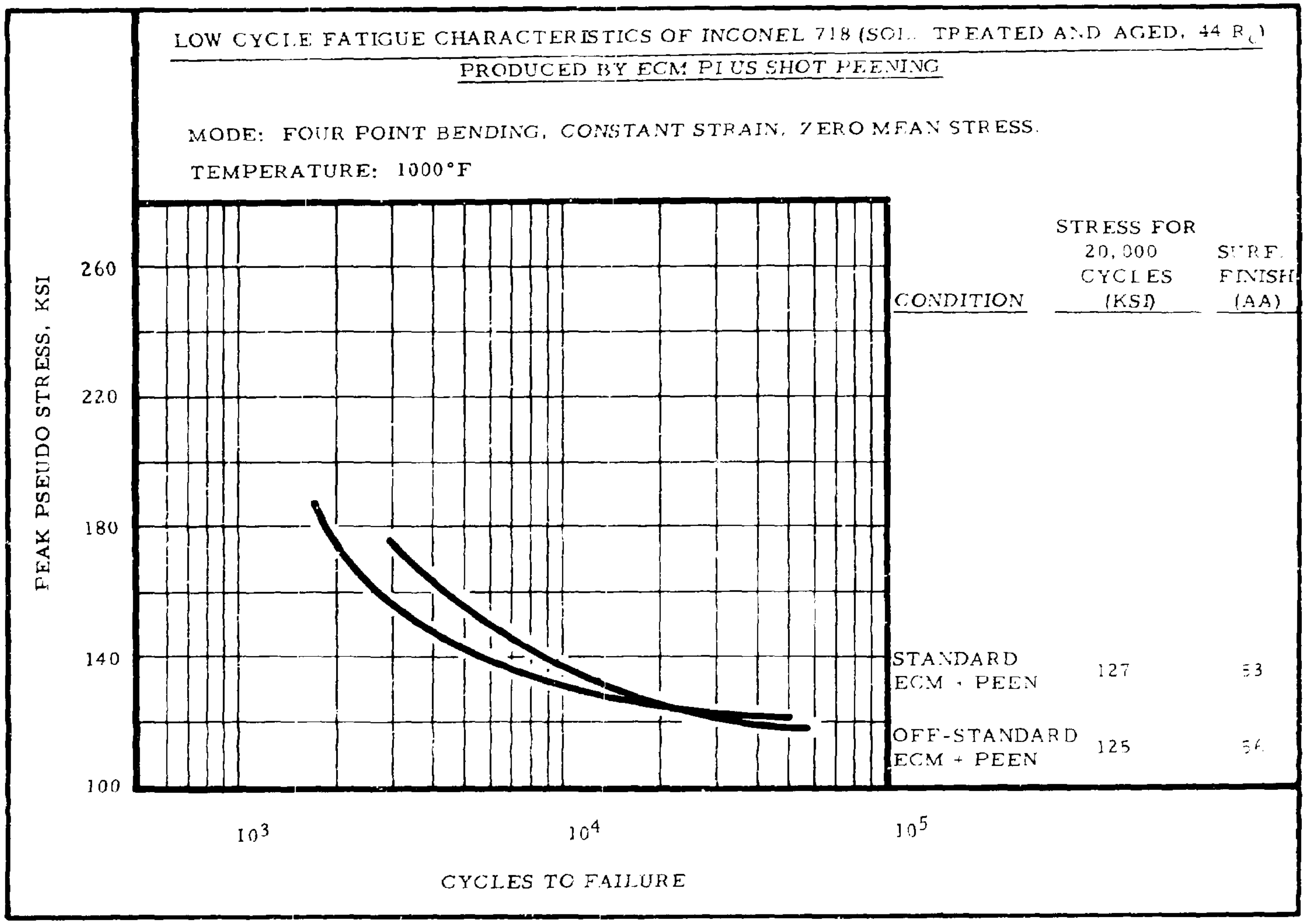


Figure 86
LOW CYCLE FATIGUE OF INCONEL 718:
ECM + SHOT PEENING

6.8 AF 95, Solution Treated and Aged, 50 R_c

The surface integrity behavior of this alloy has been explored in depth using both high cycle and low cycle tests at room temperature and 1000° F. This elevated temperature was selected as being typical of service application temperatures for the alloy.

A summary of fatigue behavior determined for the material is shown in bar graph form in Figures 87 and 88. From an examination of Figure 87, it may be seen that AF 95, like virtually all other materials, is extremely sensitive to variations in grinding practice. Fatigue strengths associated with gentle, conventional, and abusive grinding were 75, 24 and 26 ksi, respectively. Fatigue strengths associated with standard and off-standard ECM were identical, 57 ksi. Those resulting from roughing and finishing EDM were also similar, 35 versus 40 ksi.

In all cases where shot peening was applied as a post treatment, significant increases in fatigue strength resulted. This may readily be seen in Figure 87.

High cycle fatigue behavior at 1000° F shows the same relative behavior as its room temperature counterpart. Gentle versus abusive grinding resulted in endurance limits of 98 and 48 ksi, respectively. Fatigue behavior of ECM and EDM surfaces at 1000° F showed no sensitivity to standard versus off-standard or finishing versus roughing conditions.

The low cycle fatigue behavior of this alloy, summarized in Figure 88, indicates a complete lack of sensitivity of this alloy to surface variations in the ranges studied. It is evident, however, that shot peening did have a moderate effect in those instances, where comparable data are available. In the case of the EDM, for example, peening raised the stress to produce a 20,000 cycle life at 1000° F from 90 to 137 ksi. In the case of ECM, peening raised the corresponding stress from 122 to 165 ksi.

In all of the comparisons of high cycle data, it will be noted that the fatigue strengths obtained at 1000° F are higher than those determined for the corresponding room temperature condition. On the other hand, low cycle fatigue strengths determined at 1000° F are consistently lower than those obtained for the corresponding room temperature condition. These are metallurgical phenomena which have also been observed in other nickel base alloys and are discussed further in subsequent parts of this section.

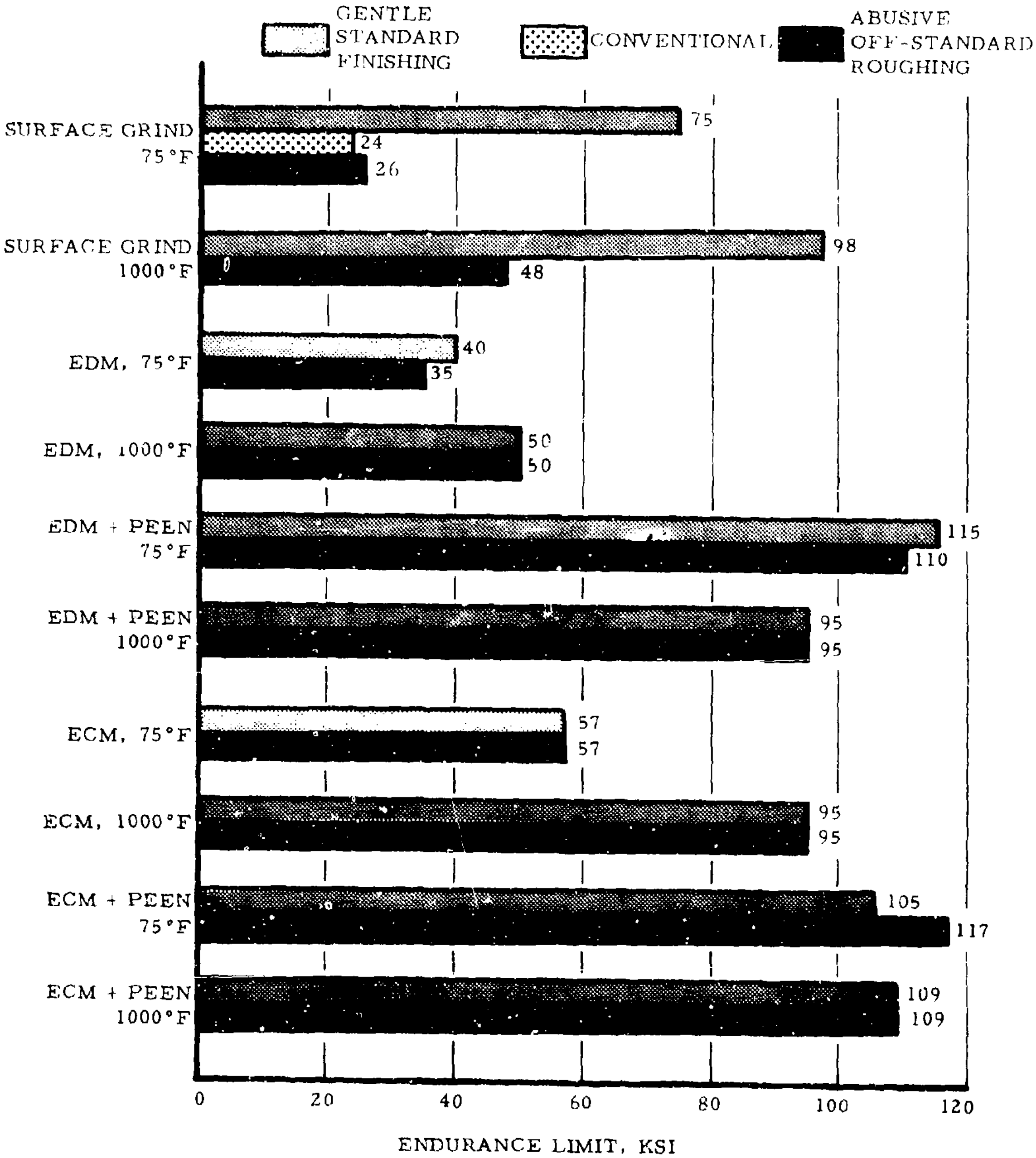


Figure 87
SUMMARY OF HIGH CYCLE FATIGUE BEHAVIOR OF AF95 (SOLUTION TREATED AND AGED, 50 R_c)

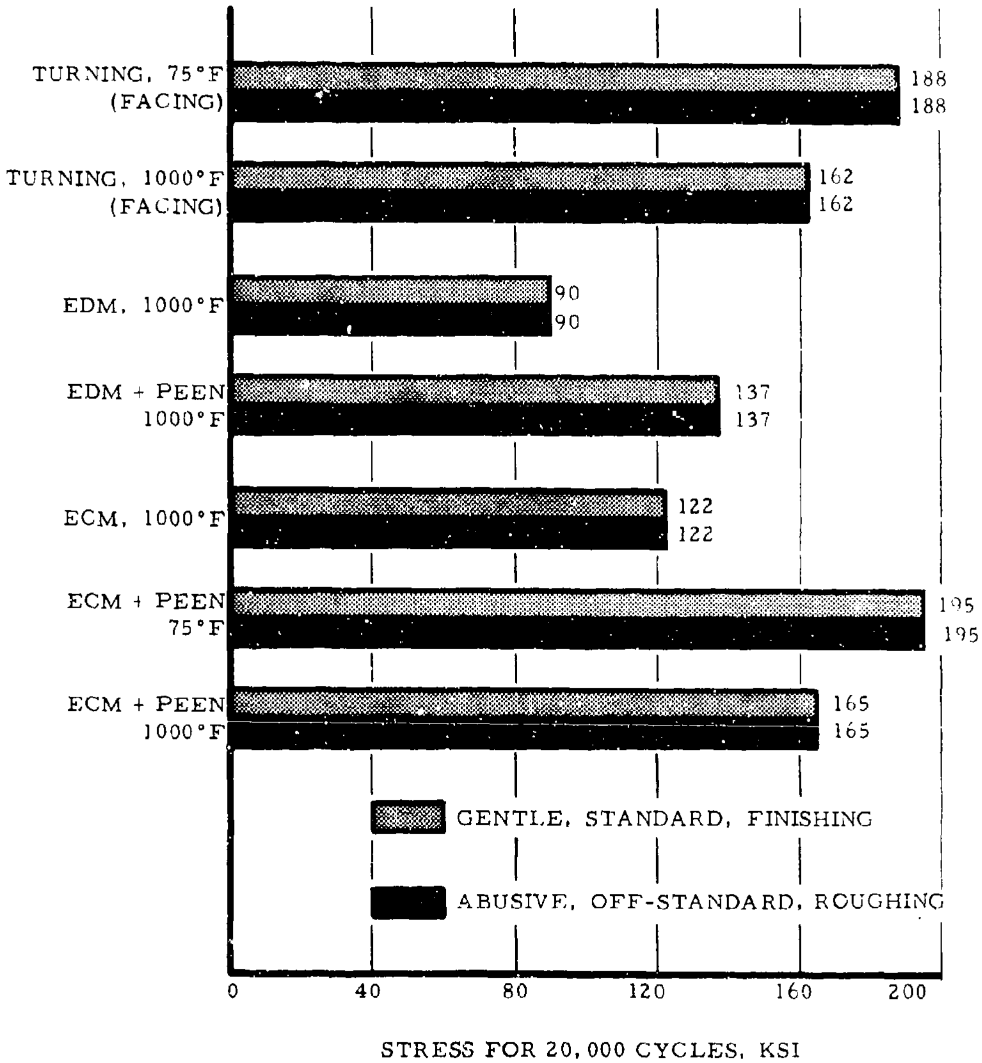


Figure 88
SUMMARY OF LOW CYCLE FATIGUE BEHAVIOR OF AF95 (SOLUTION TREATED AND AGED, 50 R_c)

6.8.1 Surface Grinding - AF 95, STA, 50 R_c

Metallography

Photomicrographs of the surface structures produced in AF 95 as a result of surface grinding under gentle, conventional, and abusive conditions are shown in Figure 89. Grinding conditions used for making these test cuts on the specimens are summarized in Table II.

Gentle grinding shows no evidence of surface alteration either from plastic deformation or localized heating. Slight evidence of surface softening to the extent of about two points R_c was observed on gently ground samples.

The conventionally ground sample as shown in Figure 89 (b), likewise is free from any evidence of plastic deformation or surface overheating. The macro surface finish as measured by stylus instruments shows the conventionally ground sample to be somewhat rougher than the gently ground sample, 41 versus 13 AA as in the figure. A very slight tendency toward hardening near the surface is indicated in Figure 89 (b). This probably is the result of a slight aging reaction associated with surface heating during grinding.

The abusively ground sample shows a somewhat rougher surface condition including a number of microscopic tears at the surface, Figure 89 (c). No visible plastic deformation or effects of overheating are evident. Microhardness data, however, indicates a subsurface hardening of up to two points R_c which is slightly greater than that observed for conventional grinding. The total depth effected was .003 to .004 inches. It is presumed that aging due to localized surface heating is probably responsible for this small hardness increase.

Residual Stress

Residual stress profiles obtained from AF 95 samples ground by gentle, conventional and abusive techniques are shown in Figure 90. Gentle grinding resulted in a shallow peak compressive stress of about 60 ksi. Both conventional and abusive grinding resulted in peak tensile stresses at the surface in excess of 160 ksi. The residual tensile stresses resulting from abusive grinding are present to a slightly greater depth than those produced by conventional grinding. This behavior is typical of that which has been found in nickel base alloys.

6.8.1 Surface Grinding - AF 95, STA, 50 R_c (continued)

High Cycle Fatigue Strength

Summaries of the high cycle fatigue strengths obtained in AF 95 are shown in Figures 91 and 92 for room temperature and 1000°F, respectively. Grinding conditions evaluated included gentle, conventional, and abusive grinding at room temperature and gentle and abusive grinding at 1000°F. The 1000°F test temperature was chosen since it represents a typical application temperature for AF 95.

The major parameters constituting the gentle, conventional, and abusive grinding conditions are: 1) the grinding wheel hardness, 2) the wheel speed, 3) the down feed, and 4) the grinding fluid, (see Table II). The importance of selecting appropriate grinding parameters is evident in the wide range of fatigue strengths observed in Figures 91 and 92.

At room temperature, Figure 91, an endurance limit at 10^7 cycles of 75 ksi was obtained for gentle grinding, while endurance limits of 24 and 26 ksi were obtained for conventional and abusive grinding, respectively. The resultant high fatigue strength of gentle grinding and the low fatigue strength of conventional and abusive grinding are probably related to the residual surface stresses resulting from grinding, although other factors may be involved. Gentle grinding resulted in peak compressive residual stresses on the order of 60 ksi while conventional and abusive grinding resulted in peak tensile residual stresses on the order of 180 ksi. Although this observation qualitatively explains the results, the quantitative relationship between fatigue strength and residual stress is at present uncertain.

Elevated temperature testing was performed because of concern over whether surface effects related fatigue strength differences observed at room temperature continue to exist in the range of operating temperatures. It has been suggested that adverse processing can relax when subjected to elevated temperature and diminish the influence of surface effects. A comparison of Figures 91 and 92 show that some diminution did occur in the fatigue strength difference at 1000°F of gentle and abusive grinding. However, even at 1000°F, abusive grinding reduced the fatigue strength relative to gentle grinding by about 50 percent.

6.8.1 Surface Grinding - AF 95, STA, 50 R_C (continued)

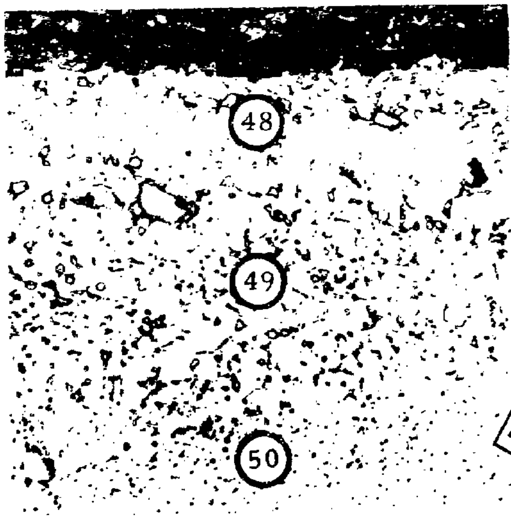
High Cycle Fatigue Strength (continued)

Therefore, the influence of surface integrity still must be considered at elevated temperature.

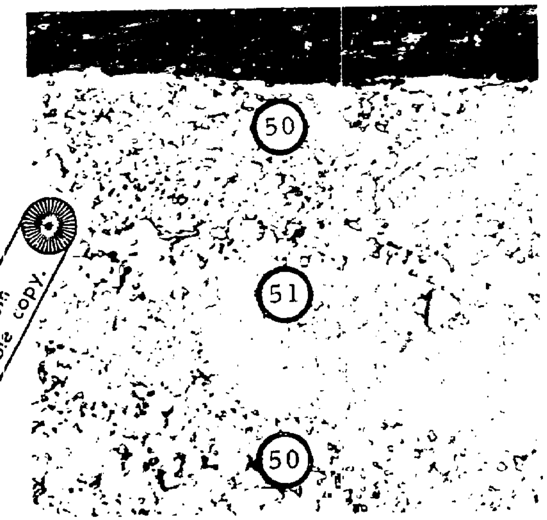
A metallurgical curiosity was observed in comparing the room temperature and elevated temperature high cycle fatigue strengths for ground AF 95. The fatigue strengths increased from 75 and 26 ksi to 98 and 48 ksi for the gentle and abusive ground conditions, respectively. Normally, reduced fatigue strength is expected with increased temperature. Low cycle fatigue strength of AF 95 did decrease with increased temperature as expected for both the turned and the shot peened ECM conditions as will be seen in Sections 6.8.2 and 6.8.4.

However, for AF 95 and other similar nickel base alloys, greater high cycle fatigue strength is sometimes observed in the intermediate or service temperature ranges than at room temperature. The increase in strength has been attributed to a thermal or strain aging reaction. Specific examples of this behavior include unpublished data on Rene' 95 barstock generated by the General Electric Company and Inconel 718 sheet fatigue data published in the 1971 Aerospace Structural Metals Handbook. In the General Electric data for gentle grinding, the endurance limit in reversed bending at 10^7 cycles was observed to increase continuously from room temperature to 1200°F. Inconel 718, on the other hand, tends to exhibit a peak in fatigue strength as a functional temperature somewhere in the 600 to 800°F temperature range.

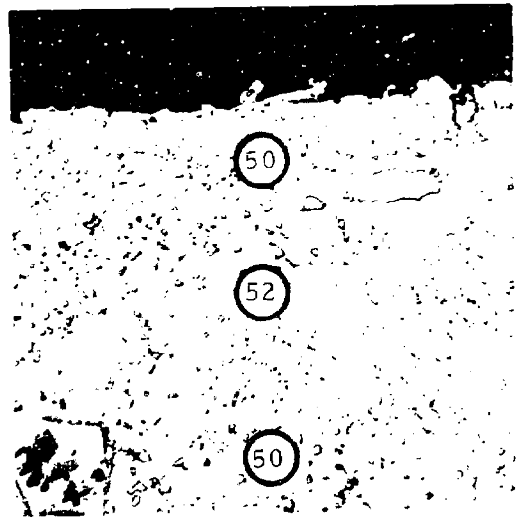
A summary of individual high cycle fatigue results for ground AF 95 is contained in Table XXII.



(a) Gentle Grinding
Surface Finish:
Perpendicular to lay: 13 AA
Parallel to lay: 12 AA



(b) Conventional Grinding
Surface Finish:
Perpendicular to lay: 41 AA
Parallel to lay: 22 AA



(c) Abusive Grinding
Surface Finish:
Perpendicular to lay: 70 AA
Parallel to lay: 31 AA

The microstructural response of AF 95 indicates a low sensitivity of this alloy to surface heating associated with grinding. Abusive grinding produced a slight increase in subsurface hardness of two points R_C. Conventional grinding produced a lesser increase, one point R_C. It is presumed that these hardness increases are due to an aging response in the alloy as a result of the localized surface heating. No plastic deformation is evident in any of these samples. Indicated hardness data are R_C values converted from Knoop microhardness measurements. Surface finish measurements are averages of readings made on all specimens from each group.

Magnification: 1000X

ORIENTATION: LONGITUDINAL GRIND. SURFACE SECTIONS PERPENDICULAR TO GRINDING LAY.

Figure 89
SURFACE CHARACTERISTICS OF AF95 (SOLUTION TREATED AND AGED, 50 R_c) PRODUCED BY SURFACE GRINDING

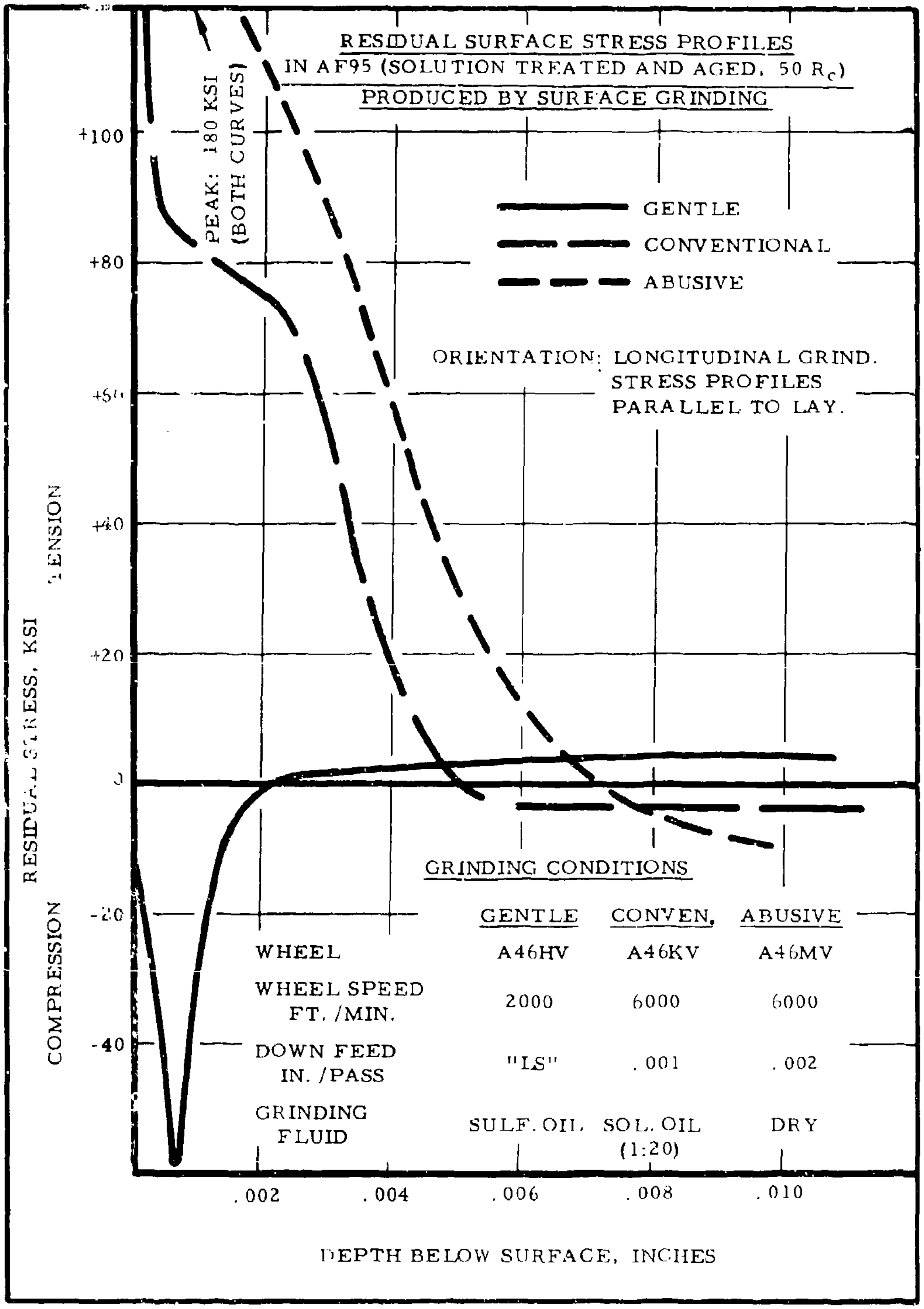


Figure 90
RESIDUAL STRESS IN AF95:
SURFACE GRINDING

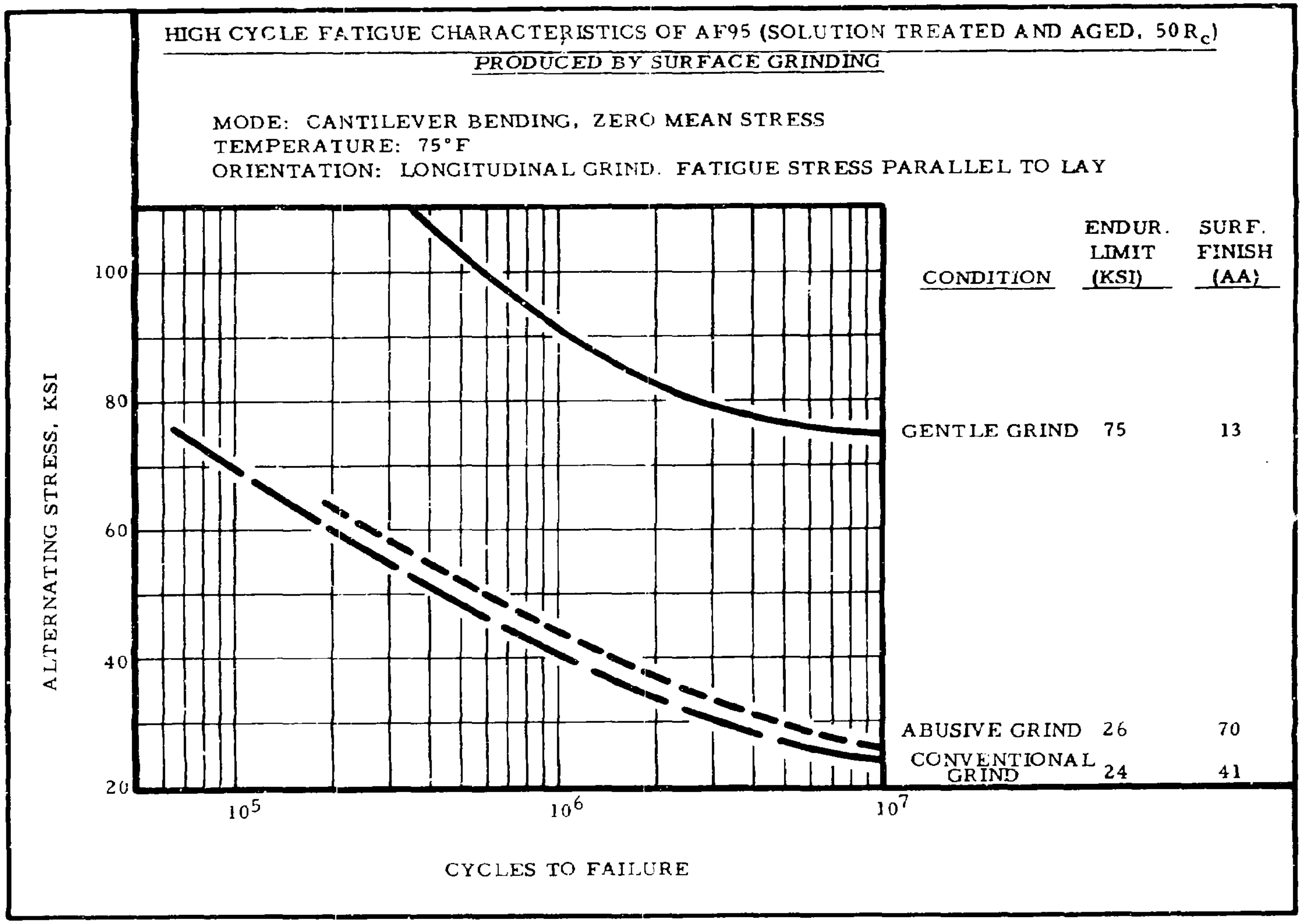


Figure 91
HIGH CYCLE FATIGUE OF AF95:
SURFACE GRINDING

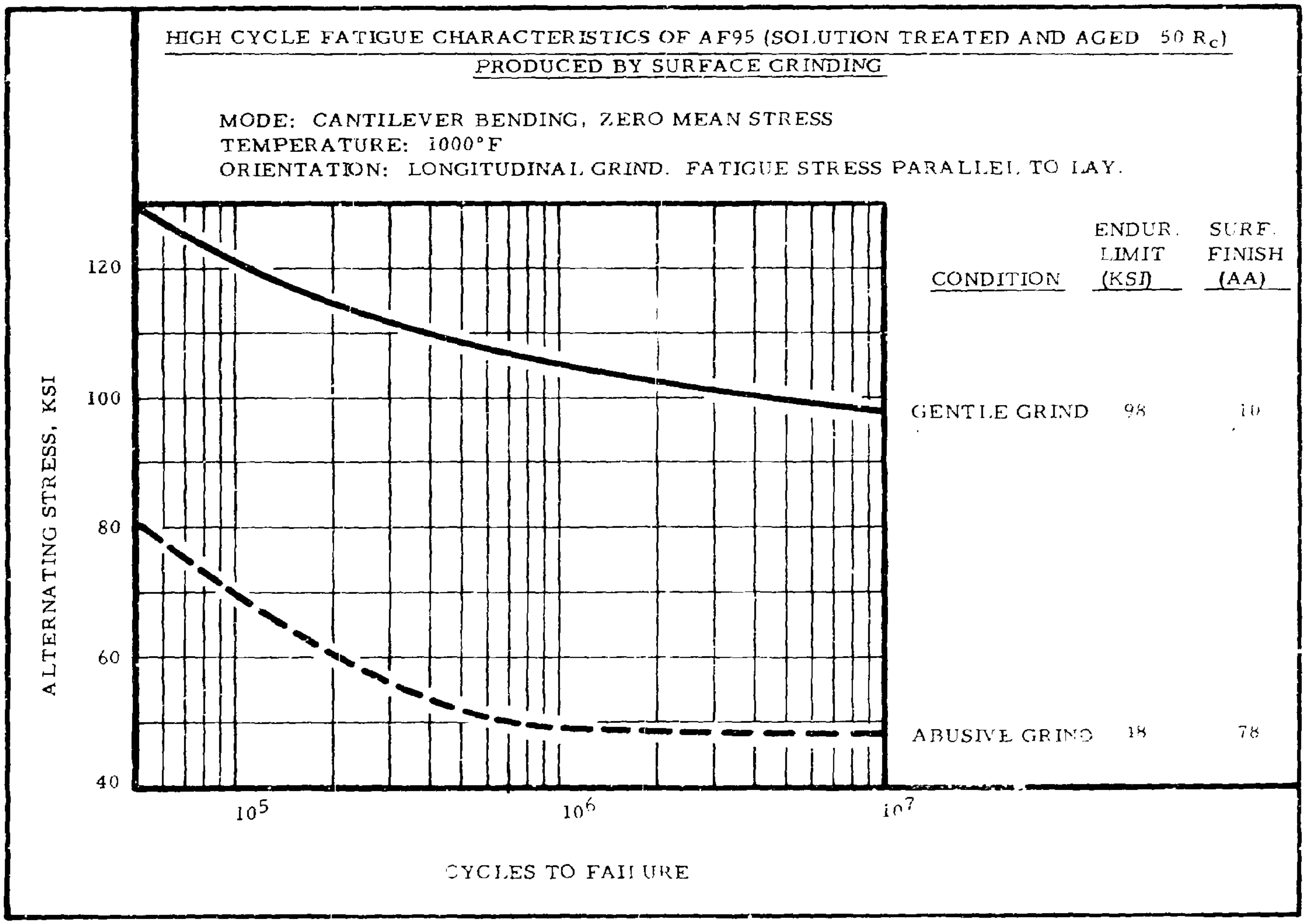


Figure 92
HIGH CYCLE FATIGUE OF AF95:
SURFACE GRINDING

6.8.2 Turning - AF 95, STA, 50 R_c

Metallography and Residual Stress

Metallography and residual stress data were not obtained for turned AF 95. It was presumed that the response of this alloy would be similar in nature to those obtained for turned Inconel 718, which is covered in Section 6.11.3.

Low Cycle Fatigue Strength

Low cycle fatigue tests were performed at room temperature and 1000°F on turned AF 95. As indicated earlier, the 1000°F temperature was chosen because it lies within the service temperature range of the alloy. Test cutting conditions for gentle and abusive turning are summarized in Table VI. The low cycle fatigue tests procedures are summarized in Appendix II-4.

The low cycle fatigue strength of turned AF 95, expressed in terms of pseudo-stress at 20,000 cycles to failure was found to be unaffected by turning parameters over the range studied. At room temperature, the strength for both gentle and abusive turning was 188 ksi (Figure 93). At 1000°F, the strength was 162 ksi (Figure 94). Note that the strength decreased with increased temperature in contrast to the general high cycle fatigue behavior. The AF 95 low cycle fatigue results were reasonable relative to those obtained for turned Inconel 718. Neither alloy exhibited sensitivity to the turning parameters used at room temperature, and while Inconel 718 exhibited very slight sensitivity to the turning parameters, AF 95 was insensitive to the parameters used. The strength at 20,000 cycles observed in both alloys were reasonably proportional to the ultimate tensile strengths; AF 95 did not show as great a strength loss with increased temperature as did Inconel 718 which reflects the lesser effect of temperature on the tensile strength of AF 95 compared to that of Inconel 718.

A summary of low cycle fatigue results for turned AF 95 is contained in Table XXIII.

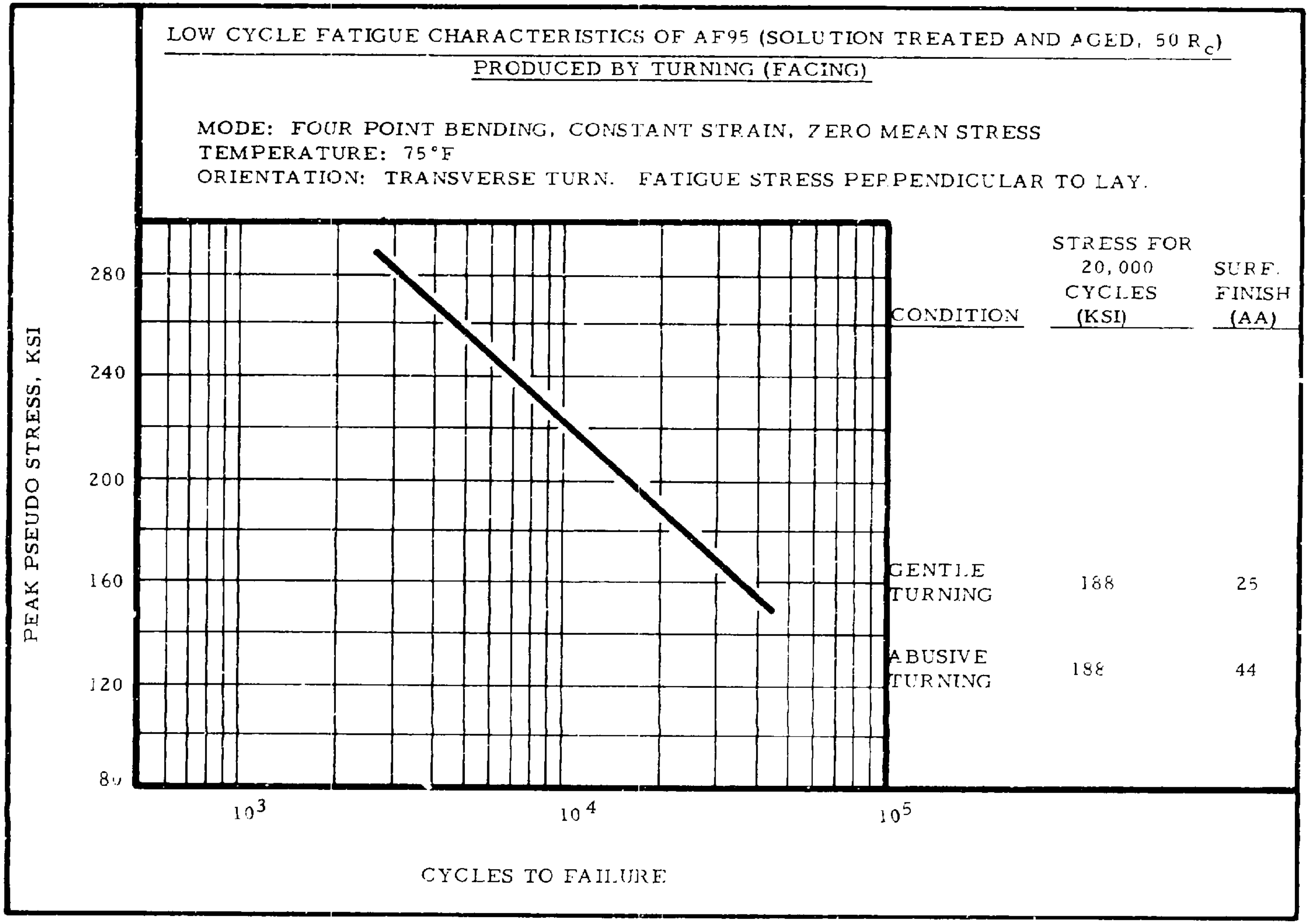
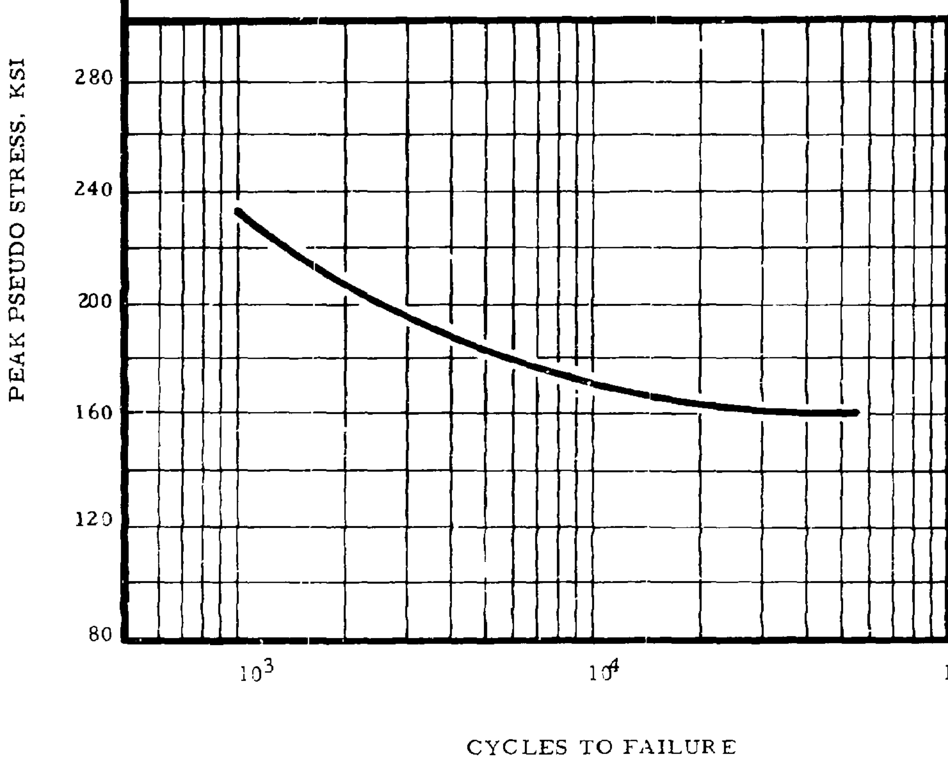


Figure 93
LOW CYCLE FATIGUE OF AF95:
TURNING (FACING)

LOW CYCLE FATIGUE CHARACTERISTICS OF AF95 (SOLUTION TREATED AND AGED, 50 R_c)

PRODUCED BY TURNING (FACING)

MODE: FOUR POINT BENDING, CONSTANT STRAIN, ZERO MEAN STRESS
TEMPERATURE: 1000°F
ORIENTATION: TRANSVERSE TURN. FATIGUE STRESS PERPENDICULAR TO LAY.



CONDITION	STRESS FOR 20,000 CYCLES (KSI)	SURF. FINISH (AA)
GENTLE TURNING	162	28
ABUSIVE TURNING	162	54

Figure 94
LOW CYCLE FATIGUE OF AF95:
TURNING (FACING)

6.8.3 EDM - AF 95, STA, 50 R_c

Metallography

Sections of AF 95 surfaces cut by finishing and roughing EDM procedures are shown in Figures 95 and 96. Figure 95 illustrates surfaces in the as-EDM'd condition, while Figure 96 illustrates EDM surfaces which subsequently have been shot peened. The test conditions used for preparation of these surfaces are summarized in Table VIII.

A recast layer is visible on all of the surfaces which is typical of the EDM process. In the case of the finishing cuts, this layer is somewhat shallower than that which is produced under roughing conditions. This is because roughing cuts involve higher current densities which cause a higher degree of localized surface heating, and hence, deposit a thicker layer. As shown in Figure 95, a slight loss in surface hardness is found in the base metal immediately beneath the recast layer. This is typically a drop not exceeding three points R_c. Where the recast layer was thick enough to be measured by microhardness techniques, its hardness on the as-EDM'd surface was found to be approximately 55 R_c. Notice also in Figure 95 (b), the presence of a crack in the EDM'd surface layer which has penetrated into the base metal. This situation would, of course, be extremely deleterious to the fatigue strength of the material.

Shot peening produced no visible metallographic differences in the surface as may be seen by comparing Figure 96 to Figure 95. Where thick enough to be measured, however, the peened recast layer was somewhat harder, averaging 59 R_c.

Residual Stress

Residual stress profiles determined on EDM'd surfaces of AF 95 are shown in Figure 97. Both roughing and finishing conditions produced shallow peak tensile stresses in the range of 120 ksi. This behavior is typical of nickel base alloys and compares very closely to that determined for Inconel 718 during a previous program (AFML-TR-70-11).

6.8.3 EDM - AF 95, STA, 50 R_c (continued)

Residual Stress (continued)

Residual stress profiles for the EDM plus shot peened condition of AF 95 were not measured. In previous effort, covered by TR-70-11, it was found that shot peening applied to EDM'd surfaces of Inconel 718 resulted in high residual compressive stresses in the surface ranging from 110 to 160 ksi. It is presumed that the effect of peening on EDM'd AF 95 would be very similar.

High Cycle Fatigue Strength

The high cycle fatigue behavior of AF 95 processed by EDM is summarized in Figures 98 and 99. Conditions examined included finishing and roughing EDM both as produced and following shot peening.

At room temperature (Figure 98), very little sensitivity to EDM variables was observed in the fatigue results; endurance limits at 10^7 cycles of 35 and 40 ksi were obtained for the roughing and the finishing EDM conditions. Both endurance limits were substantially lower than the 75 ksi endurance limit associated with gentle grinding (Figure 91). However, the 35 to 40 ksi endurance level is in excellent agreement with predictions based on the endurance limits and associated residual stresses resulting from gentle, conventional, and abusive grinding (Figures 90 and 91). Figure 98 also shows that the endurance limit of EDM processed AF 95 was significantly elevated following shot peening; endurance limits of 115 and 110 ksi were obtained for the shot peened finishing and roughing conditions, respectively. The increase in fatigue strength in this case probably resulted from the introduction of substantial residual compressive stresses into the surface of the material by shot peening.

At 1000° F (Figure 99), the 50 ksi endurance limit obtained for AF 95 finished by EDM showed very little difference in behavior between the finishing and roughing conditions. Although the individual test points separated slightly indicating higher strength for the finishing condition, the data were insufficient to justify separate treatment for the two EDM conditions. Here also, the approximately 50 percent reduction

6.8.3 EDM - AF 95, STA, 50 R_c (continued)

High Cycle Fatigue Strength (continued)

in fatigue strength at room temperature for ECM compared to gentle grinding persisted at 1000°F; 75 ksi compared to 35 to 40 ksi at room temperature and 98 ksi compared to 50 ksi at 1000°F for the gentle grinding and the ECM conditions, respective.

Similarly, the beneficial effect of shot peening of EDM prepared AF 95 also persisted at 1000°F. However, the approximate factor of two improvement in endurance limit at 1000°F, 95 ksi compared to 50 ksi, for EDM finished material was not as great as that observed at room temperature, 115 versus 40 ksi.

As previously observed for ground AF 95 (Section 6.8.1), the 1000°F endurance limit for EDM prepared AF 95 also was higher than that at room temperature. The increase in high cycle fatigue strength with increased temperature is believed to result from thermal or strain aging.

A summary of individual high cycle fatigue results for ECM prepared AF 95 is contained in Table XXII.

Low Cycle Fatigue Strength

Low cycle fatigue tests were performed at 1000°F for AF 95 finished by EDM both with and without subsequent shot peening. The 1000°F test temperature was selected because it is representative of service temperatures for this alloy. The low cycle fatigue procedures are summarized in Appendix II-4. The low cycle fatigue results for roughing and finishing EDM of AF 95 both as finished and subsequently shot peened are summarized in Figure 100. The individual low cycle fatigue results are contained in Table XXIII.

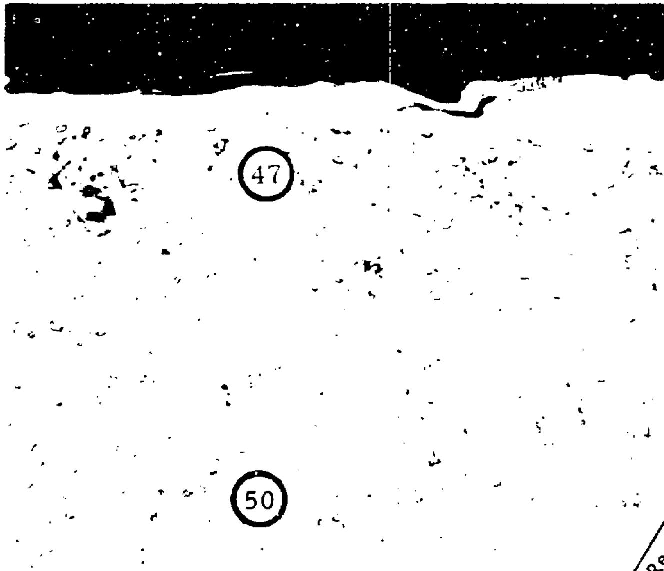
The low cycle fatigue strength of AF 95 finished by EDM expressed in terms of pseudo-stress at 20,000 cycles to failure, was unaffected by the EDM parameters used whether or not the material was subsequently shot peened. In the as-machined condition, a pseudo-stress of 90 ksi was obtained while subsequent shot peening resulted in approximately a

6.8.3 EDM - AF 95, STA, 50 R_C (continued)

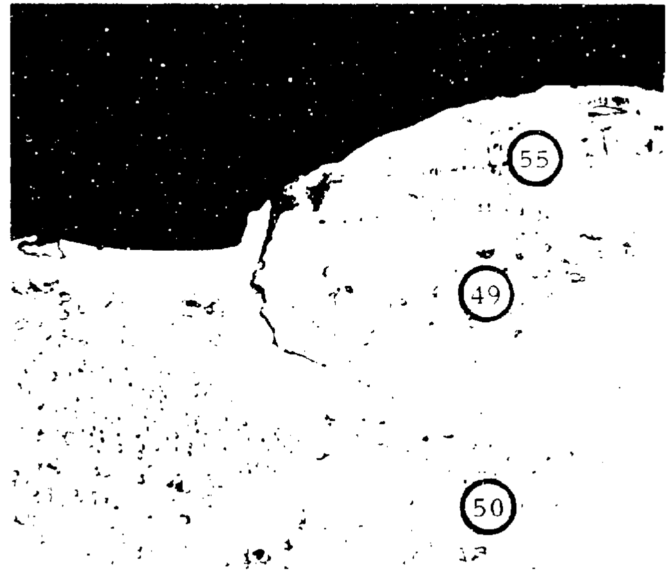
Low Cycle Fatigue Strength (continued)

50 percent increase in strength to 137 ksi. In the high cycle fatigue results discussed above, shot peening produced a twofold increase in strength. The significant improvement in low cycle fatigue behavior resulting from shot peening, while not as substantial as that observed in the high cycle fatigue results, indicates that the beneficial effects of the compressive residual stresses still remain in the low cycle fatigue range. Further, despite obvious differences in the test methods, the fatigue behavior was observed to be continuous from the low cycle to the high cycle fatigue range.

The low cycle fatigue strength of turned AF 95 (Section 6.8.2) was 162 ksi compared to 90 and 137 ksi for EDM finished AF 95 and shot peened AF 95 following EDM finishing, respectively. Metallography and residual stress data were not obtained for turned AF 95. The high fatigue strength for turned AF 95 probably results from a substantial compressive residual stress zone which is expected to be associated with the higher energy of deformation involved in turning compared to shot peening. The low cycle fatigue behavior of turned AF 95 compared to EDM finished AF 95 with and without shot peening reflects higher residual stress in that the fatigue curves did not appear to begin to converge even at a life as low as 1000 cycles.



(a) Finishing Conditions
Surface Finish: 80 AA

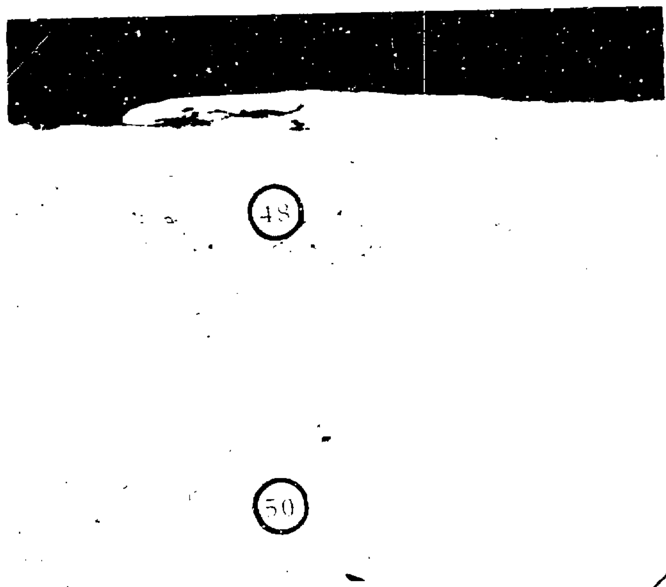


(b) Roughing Conditions
Surface Finish: 200+ AA

EDM typically shows the presence of a recast layer on the surface. As current density is increased when shifting from finishing to roughing conditions, the thickness of the recast layer also is increased. A slight softening is observed beneath the recast layer. The presence and hardness of the recast layer is probably the most significant metallographic feature. Note, also, the crack in the roughing sample which penetrates into the base metal. Indicated hardness data are R_c values converted from Knoop microhardness measurements. Surface finish measurements are averages of readings made on all specimens from each group.

Magnification: 1000X

Figure 95
SURFACE CHARACTERISTICS OF AF95 (SOLUTION TREATED AND AGED, 50 R_c) PRODUCED BY EDM



(a) Finishing Conditions
Surface Finish: 45 AA

(b) Roughing Conditions
Surface Finish: 130 AA

The addition of shot peening to the EDM surface has little effect except for a very slight smoothing action. There are no other metallographic changes evident. The hardness of the recast layer, however, 59 Rc, as noted in Figure 17b is somewhat greater than the hardness of this layer prior to shot peening. Indicated hardness data are R_c values converted from Knoop microhardness measurements. Surface finish measurements are averages of readings made on all specimens from each group.

Magnification: 1000X

Figure 96
SURFACE CHARACTERISTICS OF AF95 (SOLUTION TREATED AND AGED, 50 R_c) PRODUCED BY EDM PLUS SHOT PEENING

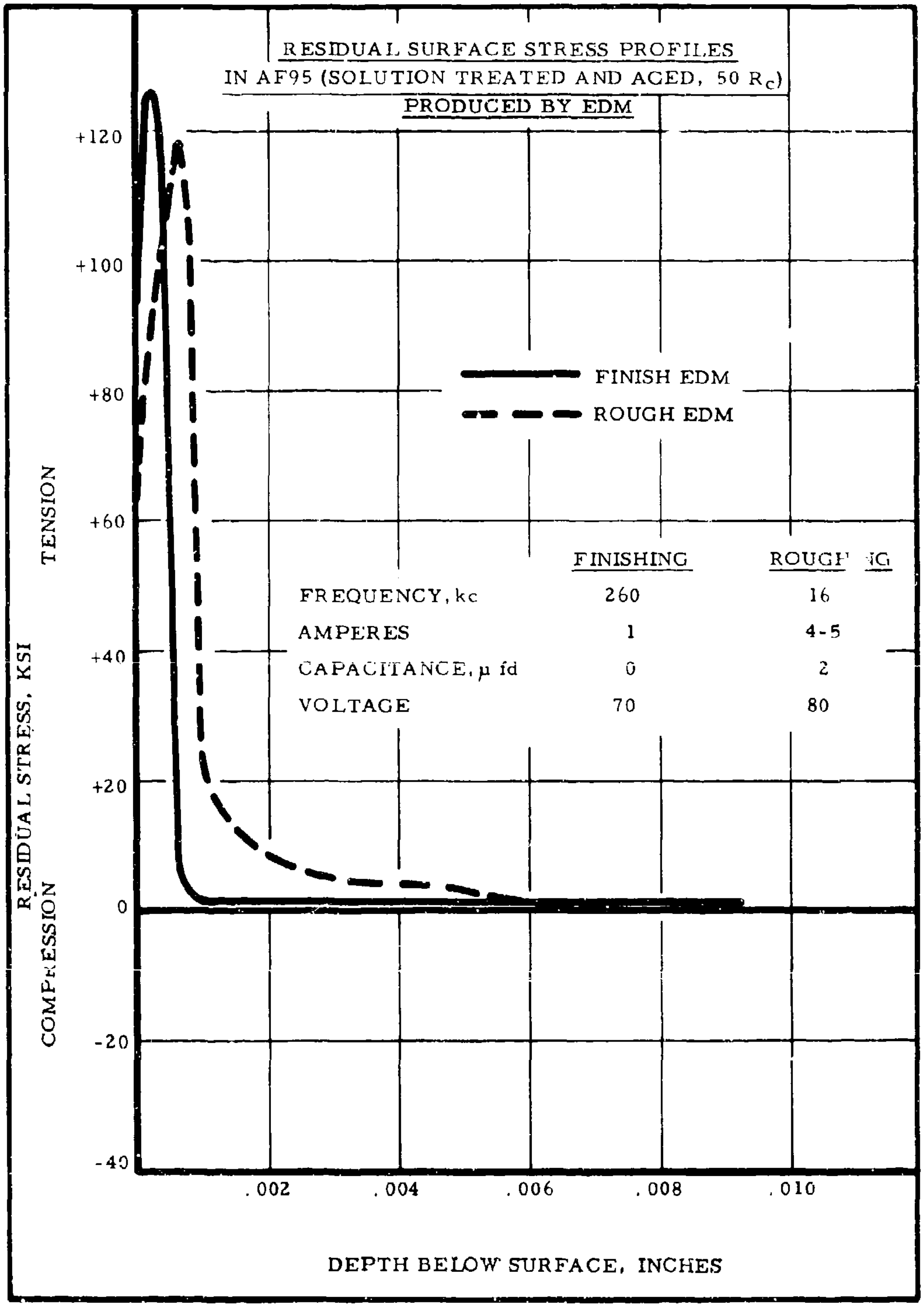


Figure 97
RESIDUAL STRESS IN AF95:
EDM

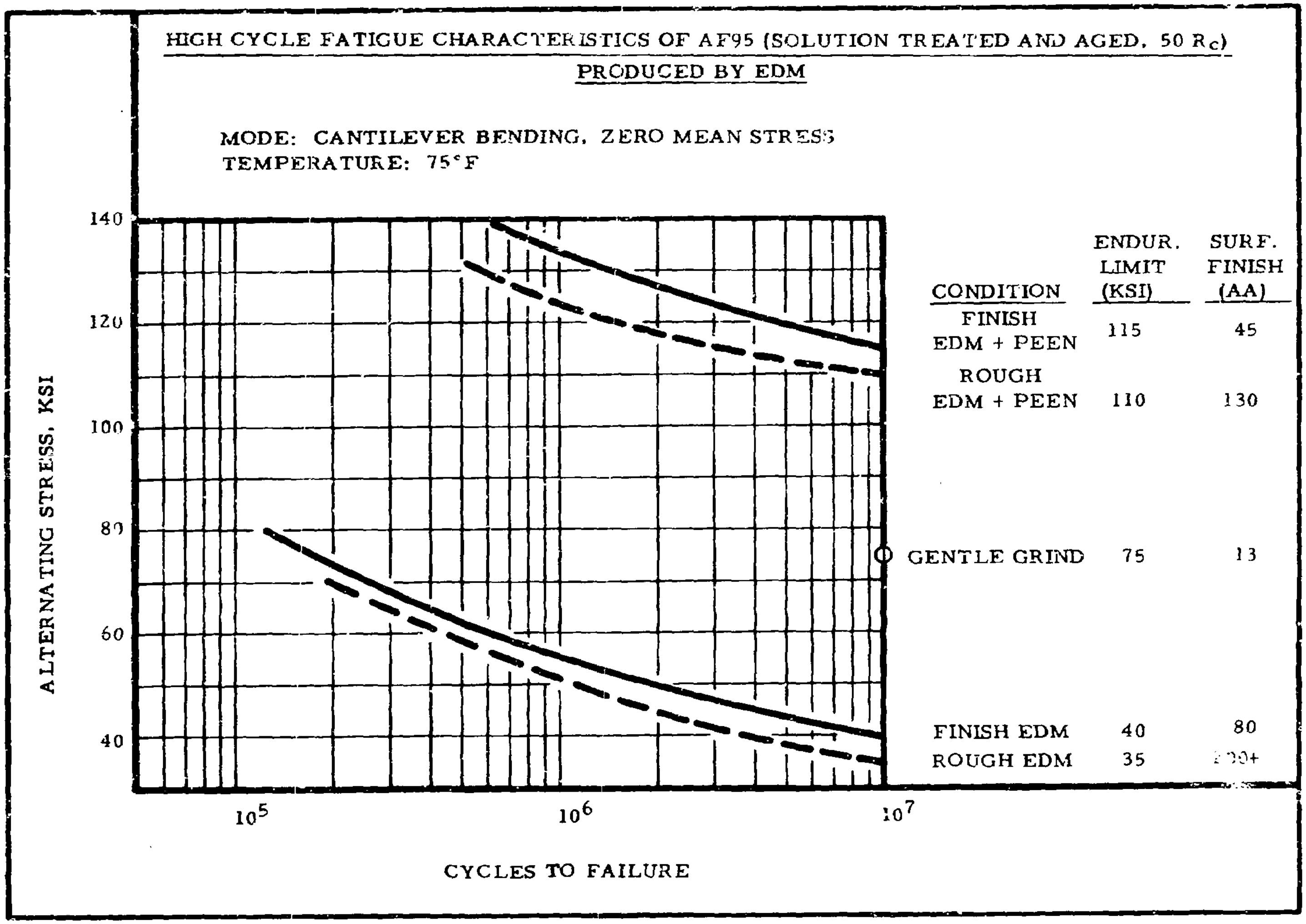


Figure 98
HIGH CYCLE FATIGUE OF AF95:
EDM

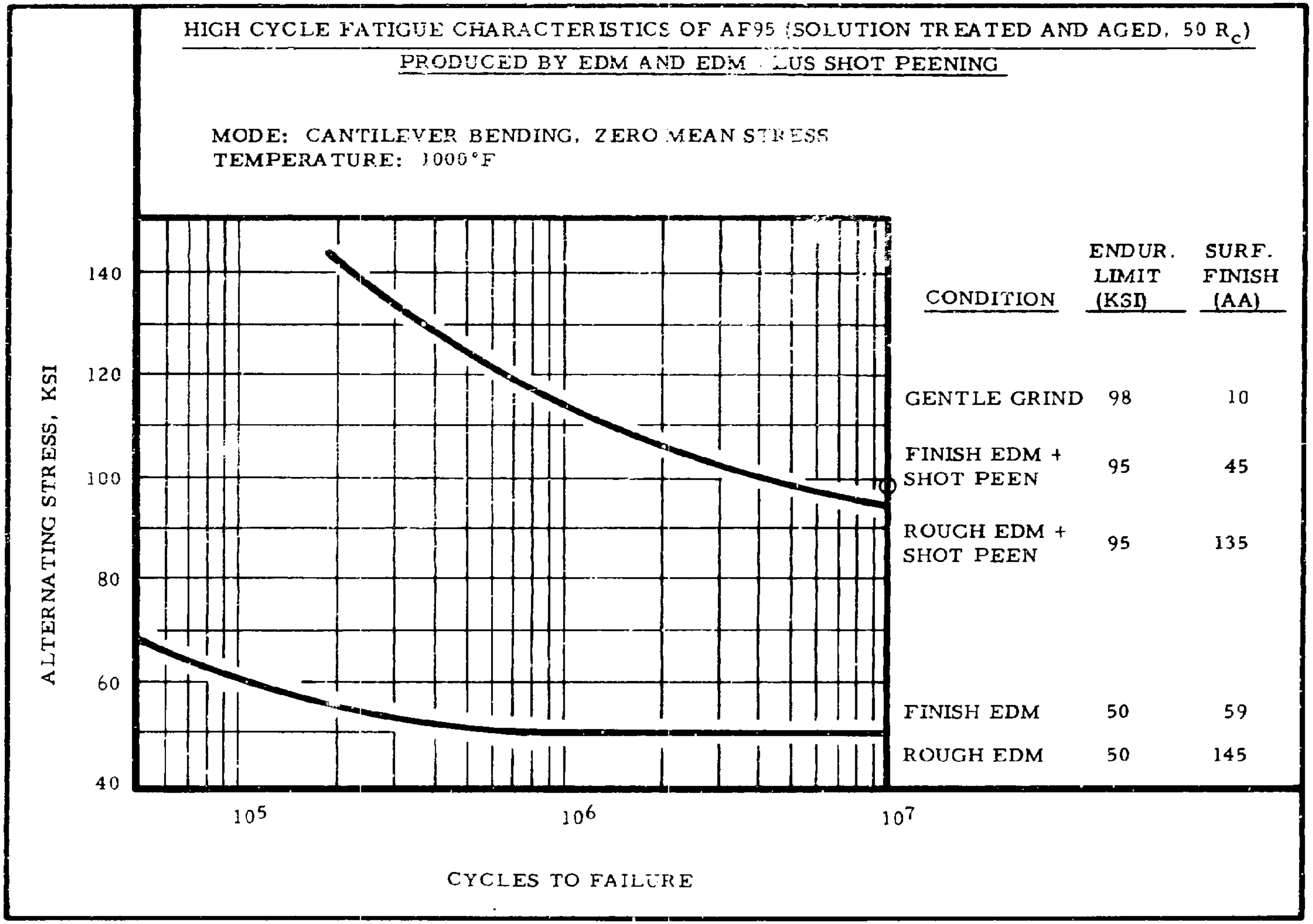
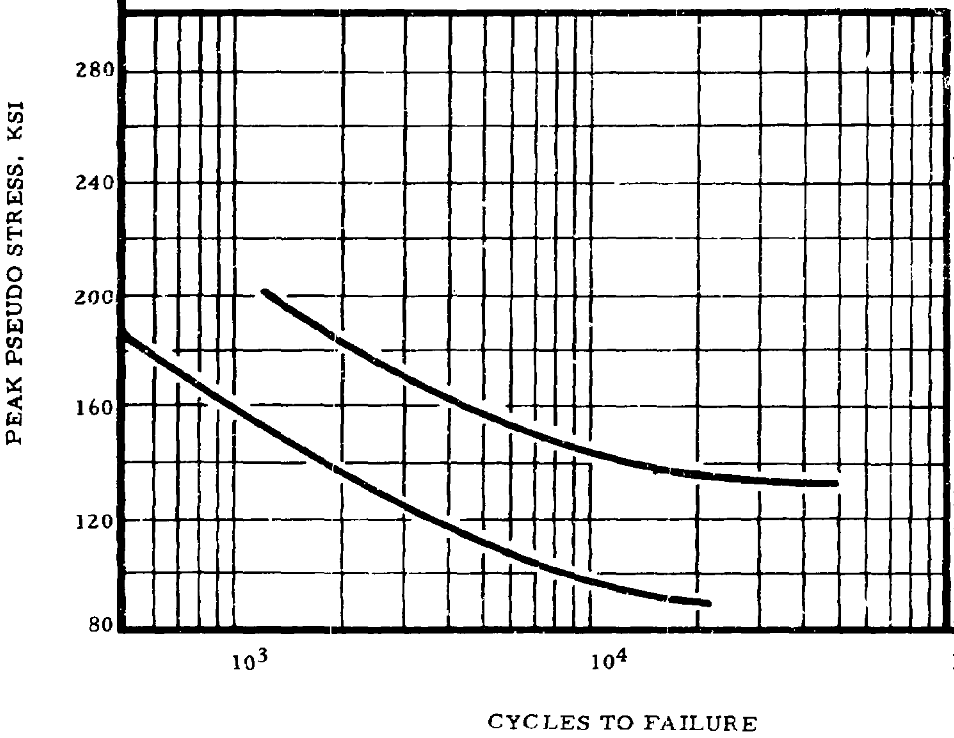


Figure 99
HIGH CYCLE FATIGUE OF AF95:
EDM AND EDM + SHOT PEENING

LOW CYCLE FATIGUE CHARACTERISTICS OF AF95 (SOLUTION TREATED AND AGED, 50 R_c)
PRODUCED BY EDM AND EDM PLUS SHOT PEENING

MODE: FOUR POINT BENDING, CONSTANT STRAIN, ZERO MEAN STRESS
TEMPERATURE: 1000°F



CONDITION	STRESS FOR 20,000 CYCLES (KSI)	SURF. FINISH (AA)
FINISH EDM + SHOT PEEN	137	81
ROUGH EDM + SHOT PEEN	137	160
FINISH EDM	90	78
ROUGH EDM	90	155

Figure 100
LOW CYCLE FATIGUE OF AF95:
EDM AND EDM + SHOT PEENING

6.8.4 ECM - AF 95, STA, 50 R_c

Metallography

Photomicrographs of cross sections through the surfaces finished by electrochemical machining of AF 95 under standard and off-standard conditions are shown in Figure 101. The ECM conditions used to produce these test cuts are summarized in Table IX.

Microscopic surface roughening typical of that produced by ECM is shown on both surfaces. However, no evidence of plastic deformation or of a disturbed surface layer is present. Slight softening not exceeding one to two points R_c was observed at .001" beneath the surface. Actually, the only apparent difference between the two surfaces is the difference in surface finish. An indication of this can be seen visually by comparing the two photomicrographs in Figure 101 and also by comparing the surface finish readings for the standard and the off-standard conditions, 41 versus 69 AA, respectively. Photomicrographs were not obtained for ECM and shot peened AF 95. It was presumed that the surface metallography would be typical of that of other ECM plus peening treatments applied to nickel base alloys, such as shown for Inconel 718 in Figure 83.

Residual Stress

A summary of the residual stress profiles present in surfaces of AF 95 finished by ECM are shown in Figure 102. Note that both conditions resulted in very low levels of residual stress, less than 10 ksi. For all practical purposes, both samples may be considered identical and stress free.

Residual stress profiles were not obtained for AF 95 shot peened following ECM finishing. It again was assumed that shot peening would produce high compressive residual stresses on the order of 160 ksi as was the case with Inconel 718 as shown in Figure 84.

High Cycle Fatigue Strength

The high cycle fatigue behavior of AF 95 processed by ECM was examined at room temperature and at 1000° F. The 1000° F test temperature represents a typical service temperature for the alloy.

6.8.4 ECM - AF 95, STA, 50 R_c (continued)

High Cycle Fatigue Strength (continued)

Conditions examined included standard and off-standard ECM conditions and both conditions subsequently shot peened. Summaries of the high cycle fatigue behavior of both conditions at room temperature and 1000° F are presented in Figures 103 and 104. Individual high cycle fatigue results are contained in Table XXII.

At room temperature (Figure 103), very little sensitivity to ECM variables was observed in the high cycle fatigue results; a 57 ksi endurance limit at 10^7 cycles was obtained for both the standard and off-standard ECM conditions. The 57 ksi endurance limit for both ECM conditions was significantly lower than the 75 ksi endurance limit associated with gentle grinding (Figure 91). However, the fatigue strength of the ECM'd conditions was in the proper proportion to those both for the gentle, conventional, and abusive grinding conditions and the EDM conditions when one considers the residual stresses resulting from each condition. As seen in Figure 103, shot peening subsequent to ECM processing increased the endurance limit to 105 and 117 ksi for the standard and off-standard conditions, respectively. No explanation can be offered at this time for the lower fatigue strength of shot peened standard ECM compared to off-standard prepared AF 95. The general 105 to 117 ksi endurance limit level was about the same as that for AF 95 shot peened following EDM finishing (Figure 98) which indicates similar residual stress profiles.

At 1000° F (Figure 104), the high cycle fatigue behavior again was insensitive to the machining variables; an endurance limit of 95 ksi was obtained for both standard and off-standard ECM prepared AF 95. Very little difference in fatigue behavior was noted between the AF 95 (95 ksi) and gentle grinding (98 ksi) conditions. It is assumed that exposure to temperature probably reduced the low, but beneficial residual compressive stresses in the AF 95 produced by gentle grinding. The beneficial effect of shot peening ECM prepared AF 95 persisted at 1000° F, but the extent (109 ksi) compared to as-ECM'd AF 95 (95 ksi) was significantly lower than at room temperature. As was noted for all other conditions of AF 95 studied, the 1000° F high cycle fatigue strength for ECM prepared AF 95 (95 ksi) was significantly higher than that for the same conditions at room temperature (57 ksi). Thermal or strain aging is believed to be responsible for this inversion of the temperature coefficient of strength.

6.8.4 ECM - AF 95, STA, 50 R_c (continued)

High Cycle Fatigue Strength (continued)

In the case of AF 95 finished by ECM, the greatest increase in strength with increased temperature was observed. Considering the relatively stress free state of the ECM'd material at room temperature, the approximately 67 percent increase in strength at 1000°F from that at room temperature may reflect the true extent of the thermal aging process for the highly worked and incompletely solutioned AF 95 cross-rolled plate used in this study.

Low Cycle Fatigue Strength

Low cycle fatigue tests were performed at room temperature and at 1000°F on ECM finished AF 95. Conditions examined included shot peened ECM finished AF 95 at room temperature and ECM finished AF 95 both with and without subsequent shot peening. The low cycle fatigue procedures are summarized in Appendix II-4. The low cycle fatigue behavior is summarized in Figure 105 and 106. Individual low cycle fatigue results are contained in Table XXIII.

The low cycle fatigue strength of shot peened ECM finished AF 95 expressed in terms of pseudo-stress at 20,000 cycles to failure, was insensitive to the ECM variables prior to shot peening; a strength of 195 ksi was observed at room temperature (Figure 105), while a strength of 165 ksi was observed at 1000°F (Figure 106). At 1000°F, the low cycle fatigue strength for the ECM finished AF 95 also was insensitive to the process parameters; a strength of 122 ksi was obtained for both the standard and the off-standard ECM conditions (Figure 106). Note that increased temperature decreased the strength of shot peened ECM finished AF 95, while shot peening increased the strength of ECM prepared AF 95 at 1000°F. Both results were consistent with the observed high cycle fatigue behavior detailed above.

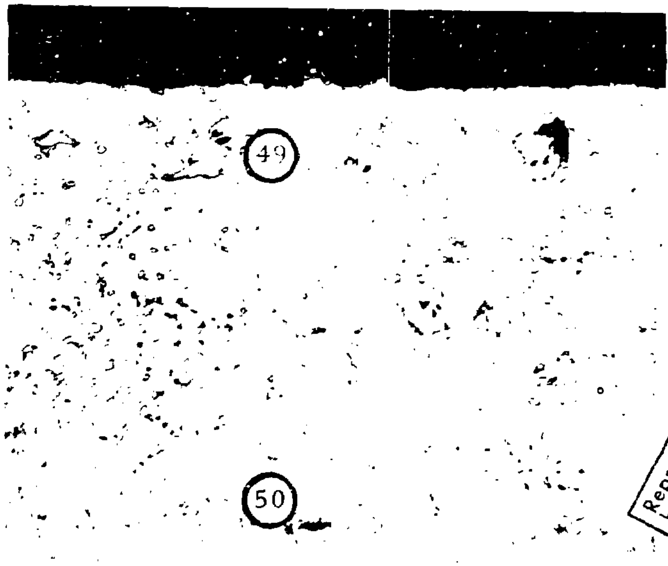
As this last observation indicates, a continuous curve extending from low to high cycle fatigue behavior was observed both for as-ECM and shot peened ECM prepared AF 95. In addition, the data overall suggest a decrease in the beneficial effect of shot peening at either very low lives or very high strain ranges. Consistent with the high cycle fatigue results, ECM prepared AF 95 exhibited greater 1000°F low cycle fatigue strength (165 ksi) than EDM finished AF 95 (137 ksi), compare Figures 100 and 103.

6.8.4 ECM - AF 95, STA, 50 R_c (continued)

Low Cycle Fatigue Strength (continued)

Following shot peening, the fatigue strength of ECM prepared AF 95 was essentially identical to that of turned AF 95 both at room temperature and at 1000°F; when individual test points were plotted, the two conditions appeared indistinguishable.

From the basic consistency of the results, one could infer the general ranking of machining processes in terms of fatigue strength to be in ascending order: 1) conventional or abusive grinding, 2) EDM, 3) ECM, 4) gentle grinding, and 5) turning. Shot peening generally resulted in strength equivalent to that of turned AF 95 irrespective of the method of processing.



(a) Standard Conditions
Surface Finish: 41 AA

(b) Off-Standard Conditions
Surface Finish: 69 AA

No evidence of surface alteration or overheating is shown in the microstructures. Microhardness data indicated a slight softening at the surface as indicated on the photomicrographs. The only apparent difference is one of surface roughness which is visible and noted above. Indicated hardness data are R_C values converted from Knoop microhardness measurements. Surface finish measurements are averages of readings made on all specimens from each group.

Magnification: 1000X

Figure 101
SURFACE CHARACTERISTICS OF AF95 (SOLUTION TREATED AND AGED, 50 R_c)
PRODUCED BY ECM

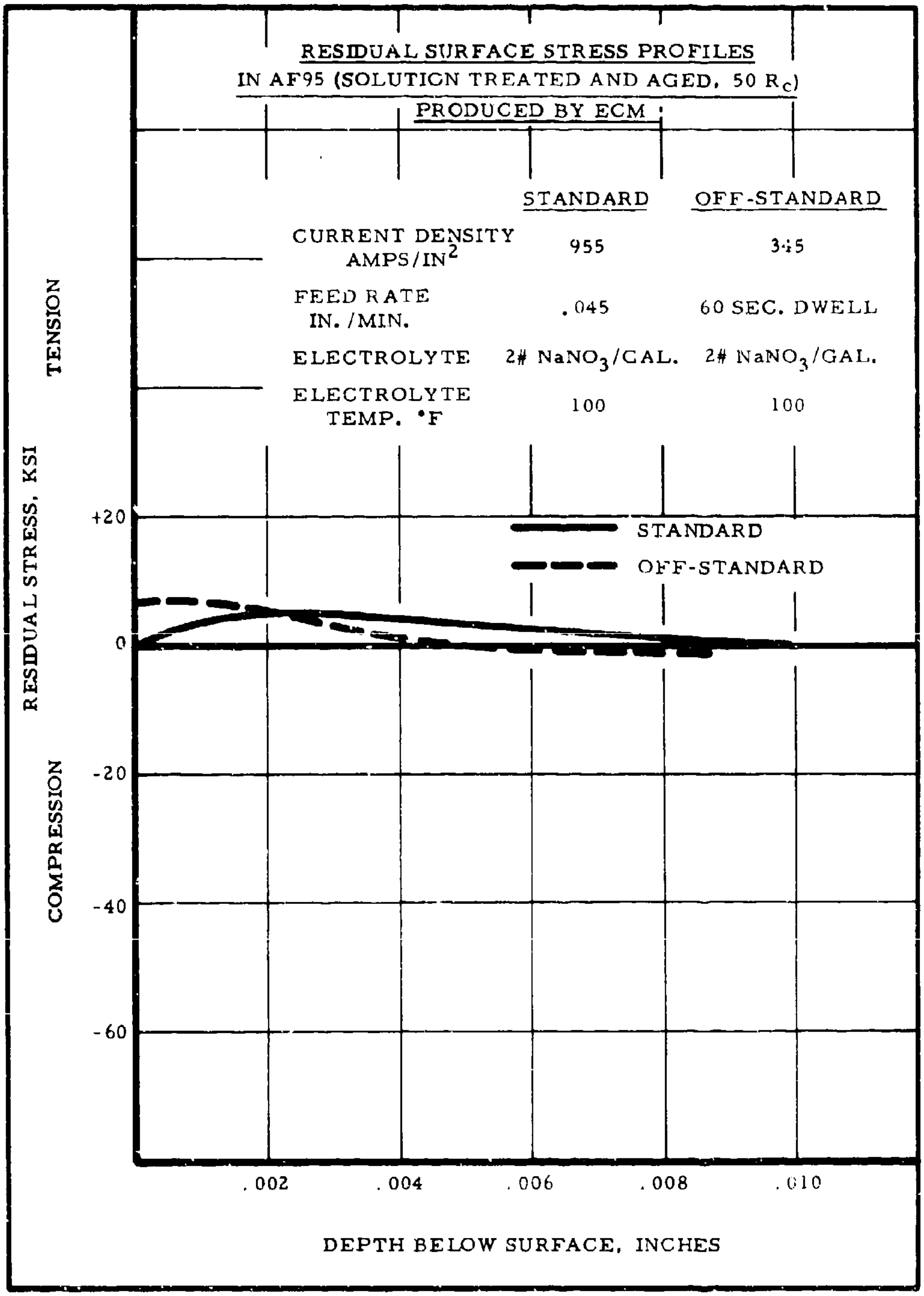


Figure 102
RESIDUAL STRESS IN AF95:
ECM

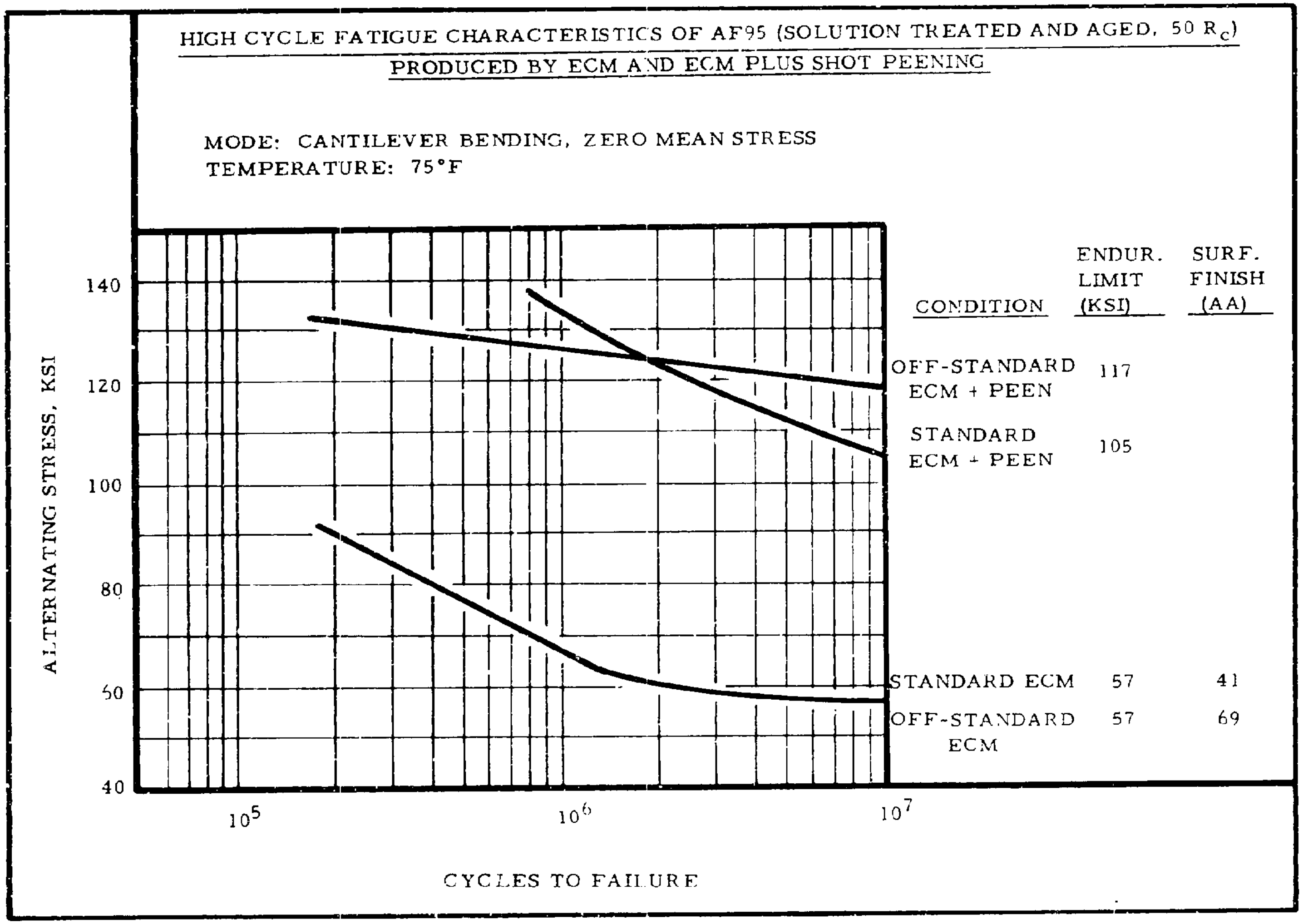


Figure 103
HIGH CYCLE FATIGUE OF AF95:
ECM AND ECM + SHOT PEENING

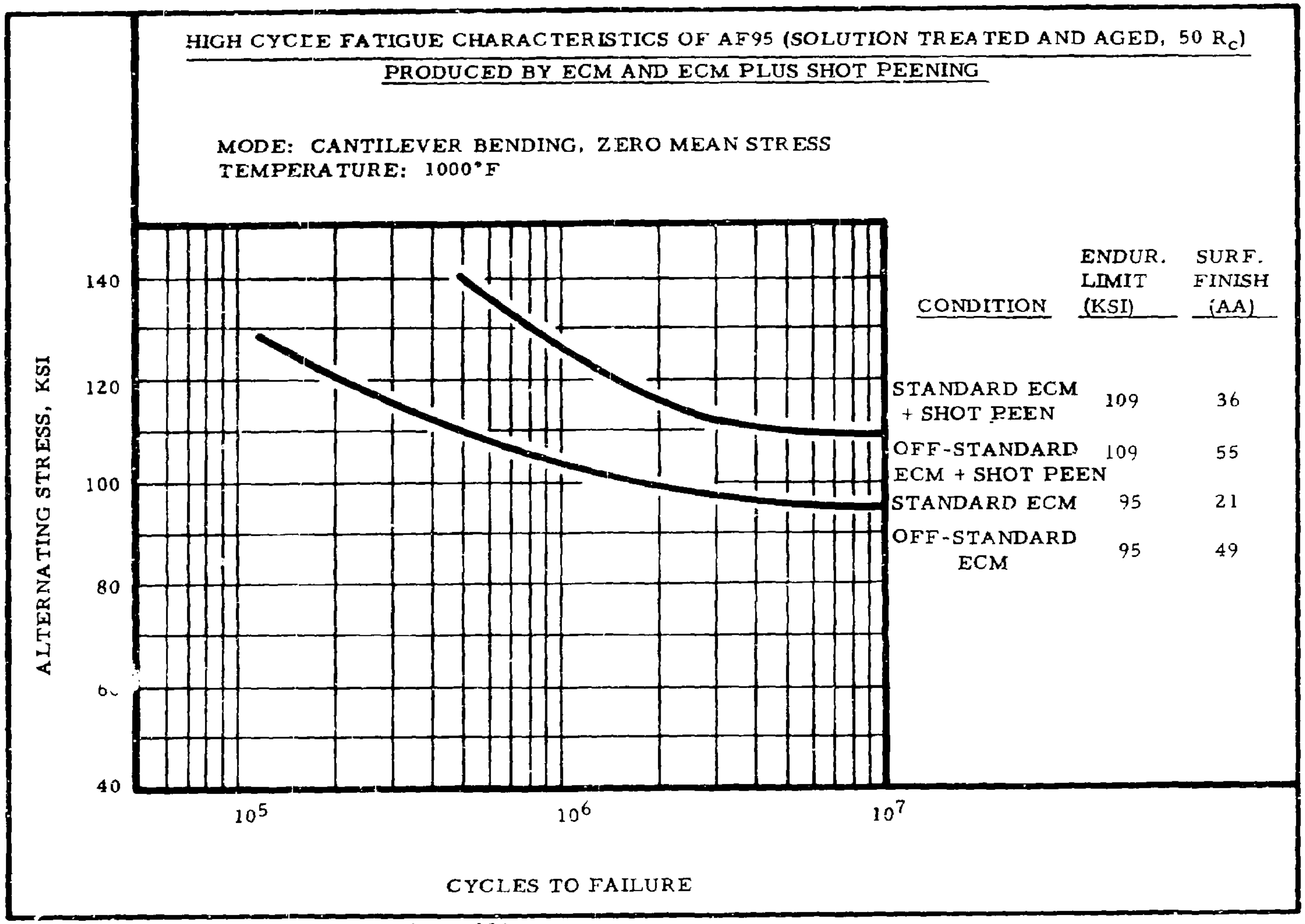


Figure 104
HIGH CYCLE FATIGUE OF AF95:
ECM AND ECM + SHOT PEENING

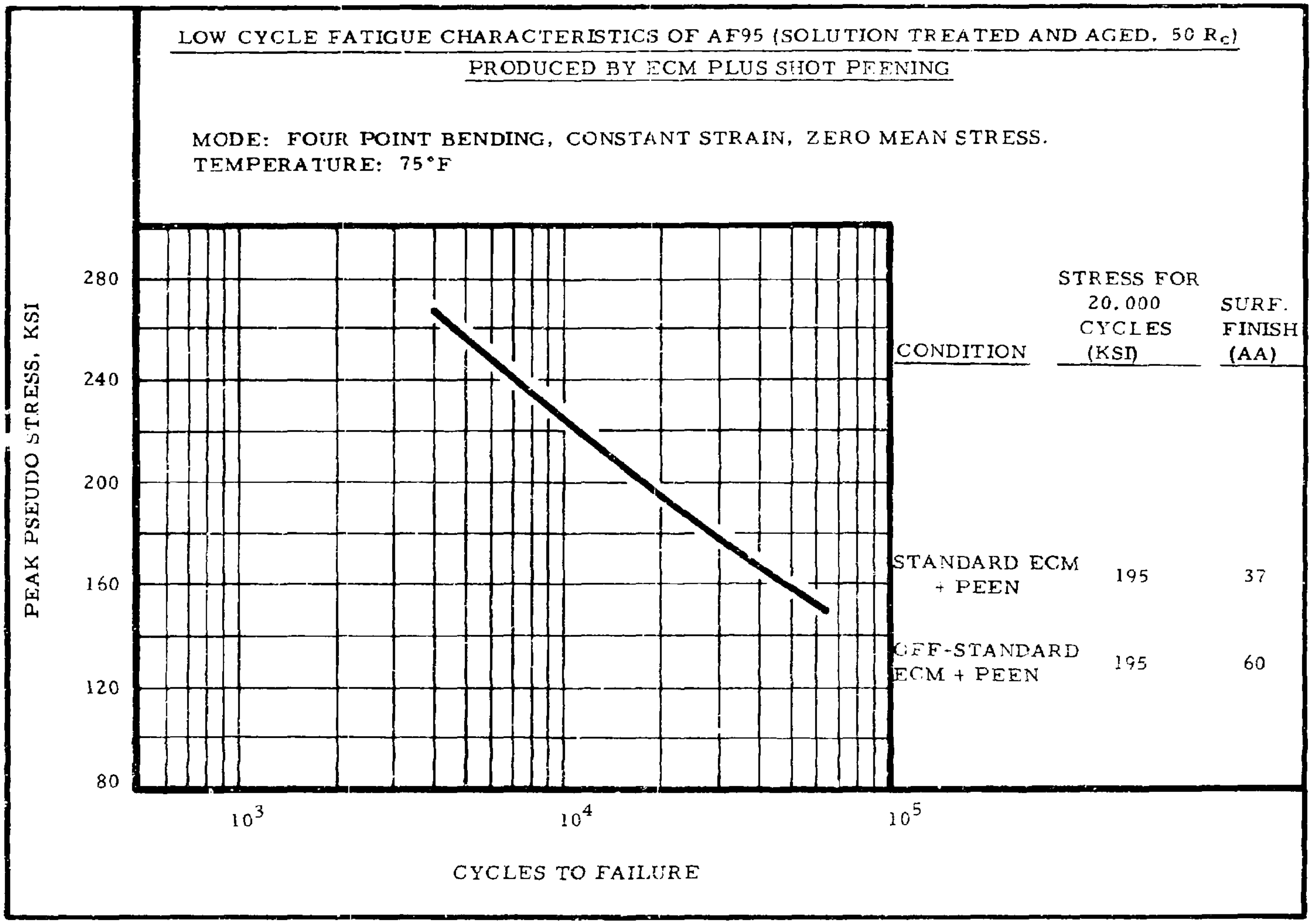
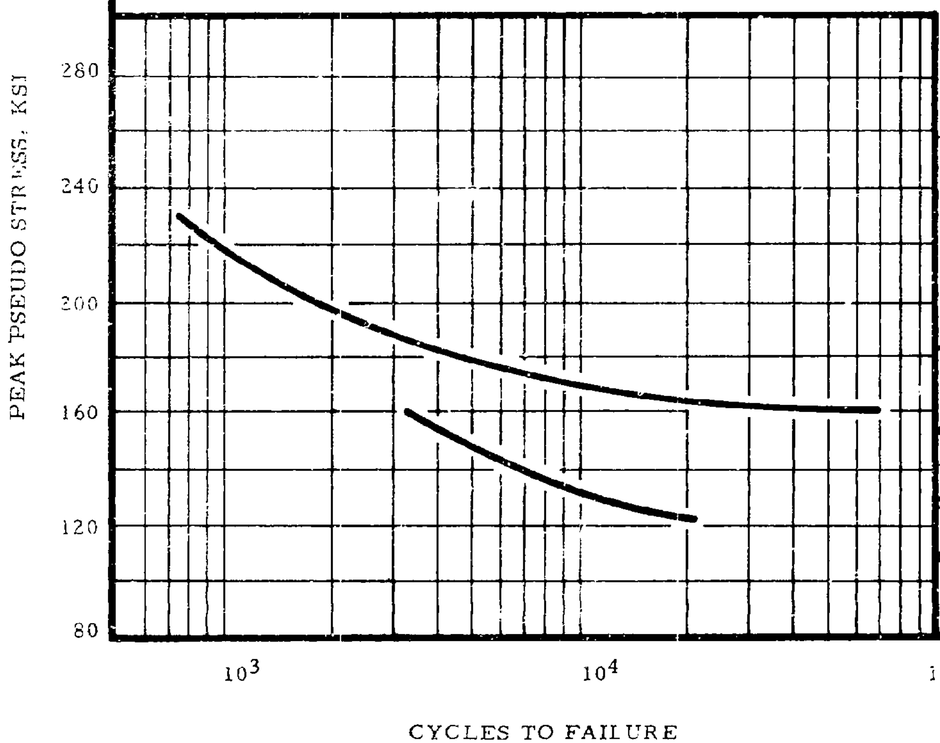


Figure 105
LOW CYCLE FATIGUE OF AF95:
ECM + SHOT PEENING

LOW CYCLE FATIGUE CHARACTERISTICS OF AF95 (SOLUTION TREATED AND AGED, 50 R_c)

PRODUCED BY ECM AND ECM PLUS SHOT PEENING

MODE: FOUR POINT BENDING, CONSTANT STRAIN, ZERO MEAN STRESS
TEMPERATURE: 1000°F



CONDITION	STRESS FOR 20,000 CYCLES (KSI)	SURF. FINISH (AA)
STANDARD ECM + PEEN	165	42
OFF-STANDARD ECM + PEEN	165	62
STANDARD ECM	122	42
OFF-STANDARD ECM	122	69

Figure 106
LOW CYCLE FATIGUE OF AF95:
ECM AND ECM + SHOT PEENING

6.9 AF2-1DA, Solution Treated and Aged, 46 R_c

A brief study of the surface integrity response of AF2-1DA was conducted. Only sufficient checks were run to verify the belief that this alloy would behave approximately like AF 95. In comparing a summary of the fatigue data developed for AF2-1DA as shown in Figure 107, with that developed for AF 95, Figure 87, the validity of this assumption is confirmed.

Typical of other high temperature nickel base alloys, the AF2-1DA shows a most pronounced sensitivity to surface grinding variables. Endurance limits resulting from gentle, conventional, and abusive grinding were 70, 25 and 20 ksi, respectively. EDM and ECM exhibited their usual characteristic levels, but with little difference in either associated with different cutting parameters.

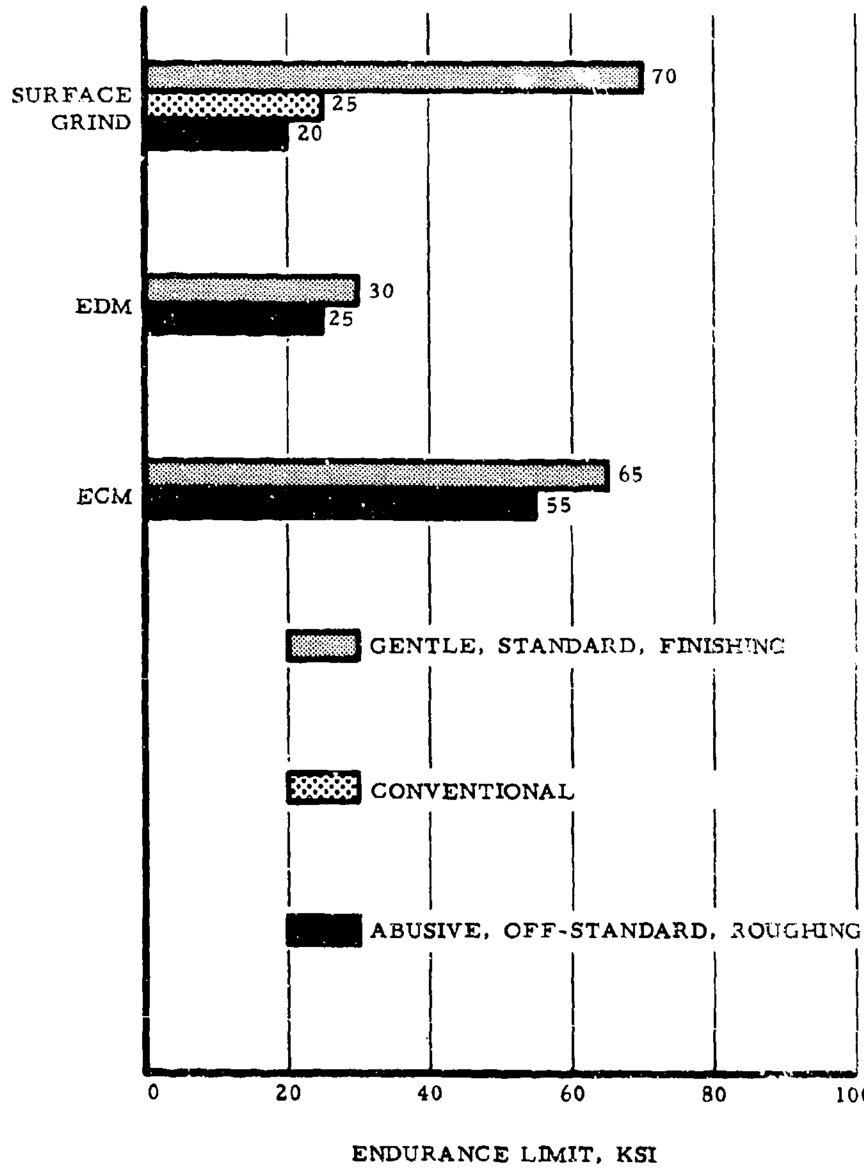


Figure 107
SUMMARY OF HIGH CYCLE FATIGUE BEHAVIOR OF AF2-1DA (SOLUTION TREATED AND AGED, 46 R_c)

6.9.1 Surface Grinding - AF2-1DA, STA, 46 R_C

Metallography

Photomicrographs of cross sections of surfaces produced in this alloy by grinding are shown in Figure 108. Typical of the higher strength nickel alloys, this material shows little or no sensitivity to surface heating from grinding as can be judged by the change in microstructure.

The gently ground sample is completely free of plastic deformation or any indication of a surface layer alteration. Microhardness data also indicated no change in microhardness as a result of grinding.

The conventional sample shown in Figure 108 (b) shows very thin random patches of deformation at the surface. The effect, however, is quite shallow and there is no general change in microstructure. A slight increase in surface hardness, however, amounting to about 2 points R_C was found at the .001" level. This is probably due to additional aging which occurred as a result of localized heating during grinding. The abusively ground sample, Figure 108 (c) shows a degree of roughening which can be seen in the microstructure and which is born out by surface finish readings. Thin patches of disturbed metal are also evident on this surface. The most significant feature, however, is an increase in hardness of up to 5 points R_C at depths as great as .004" beneath the surface. Presumably this hardness increase is the result of aging due to localized heating during grinding. As would be expected, the effect is greater in the case of the abusive grinding than was observed for gentle grinding.

Residual Stress

Residual stress profiles resulting from gentle, conventional, and abusive grinding of AF2-1DA are shown in Figure 109. This alloy is extremely sensitive to variations in grinding as evidenced by the high levels of residual stress observed. Gentle grinding produced peak compressive stresses of approximately 80 ksi. The total depth affected by gentle grinding is approximately .004". Conventional and abusive grinding resulted in peak tensile stresses of 200 and 300 ksi, respectively.

6.9.1 Surface Grinding - AF2-1DA, STA, 46 R_c (continued)

Residual Stress (continued)

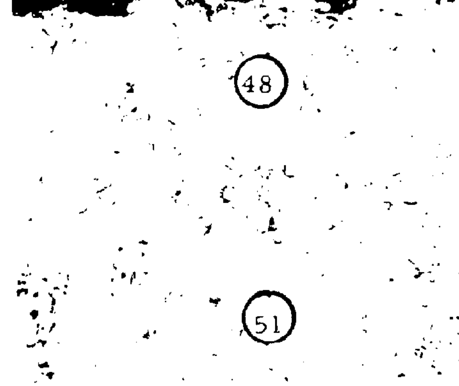
This general behavior is typical of that exhibited by high strength nickel alloys. However, the magnitude of the peaks, both compressive and tensile, are somewhat greater than have been observed in other materials under similar variations in processing.

High Cycle Fatigue Strength

The high cycle fatigue behavior of this alloy as a result of surface grinding variables is summarized in Figure 110. The endurance limit of 10^7 cycles associated with gentle grinding was approximated as 70 ksi. Endurance limits associated with conventional and abusive grinding were 25 and 20 ksi, respectively. This range of fatigue response, showing pronounced degradation of properties to be associated with conventional and abusive grinding is typical of that found for other nickel base alloys. A detailed summary of test data is included in this report as Table XXIV.

(a) Gentle Grinding
Surface Finish:
Perpendicular to lay: 10 AA
Parallel to lay: 6 AA

(b) Conventional Grinding
Surface Finish:
Perpendicular to lay: 15 AA
Parallel to lay: 6 AA



(c) Abusive Grinding
Surface Finish:
Perpendicular to lay: 24 AA
Parallel to lay: 10 AA

The surface structures of AF2-1DA show no visible sensitivity of the alloy to surface heating typically associated with grinding. Gentle grinding, furthermore, produced no detectable change in microhardness. Conventional grinding showed a surface hardness increase of approximately two points R_c at .001 in. beneath the surface. Abusive grinding showed a hardness increase of up to five points R_c for depths to .004 in. beneath the surface. This hardness increase is assumed due to an aging response as a result of localized heating. Indicated hardness data are R_c values converted from Knoop microhardness measurements. Surface finish measurements are averages of readings made on all specimens from each group.

Magnification: 1000X

ORIENTATION: LONGITUDINAL GRIND. SURFACE SECTIONS PERPENDICULAR TO GRINDING LAY.

Figure 108
SURFACE CHARACTERISTICS OF AF2-1DA (SOLUTION TREATED AND AGED, 46 R_c) PRODUCED BY SURFACE GRINDING

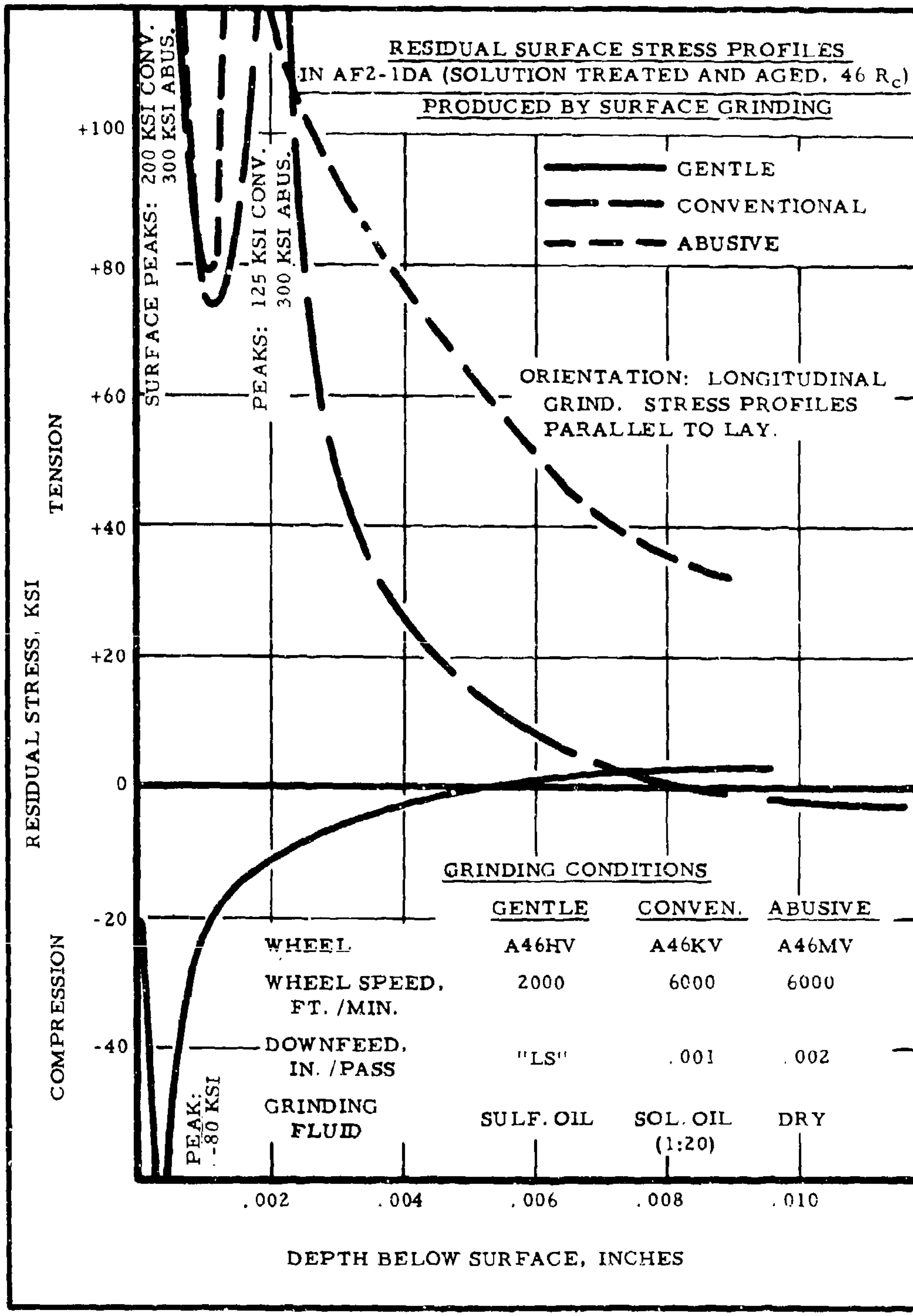


Figure 109
RESIDUAL STRESS IN AF2-1DA:
SURFACE GRINDING

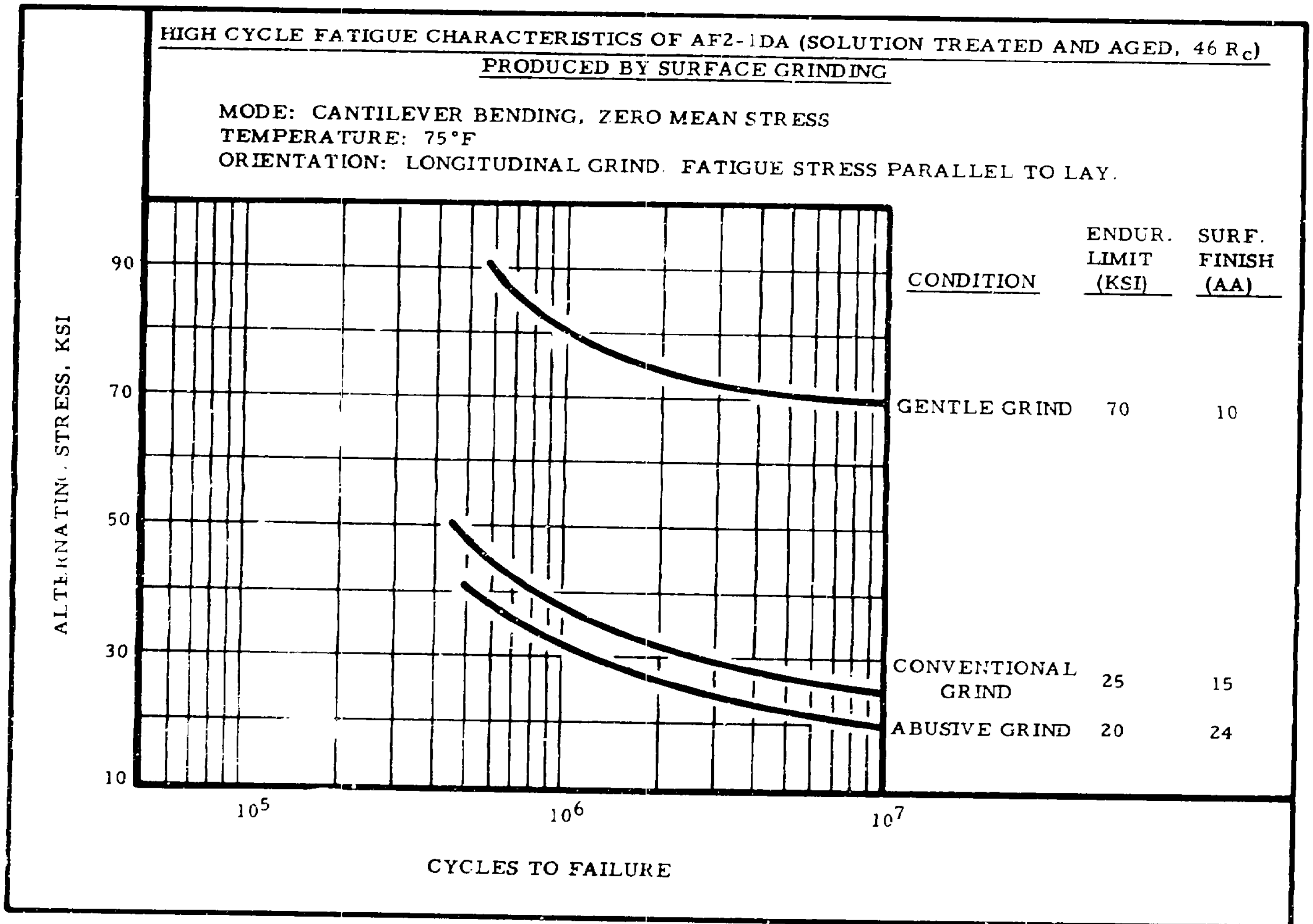


Figure 110
HIGH CYCLE FATIGUE OF AF2-1DA:
SURFACE GRINDING

6.9.2 EDM - AF2-1DA, 46 R_c

Metallography

Surfaces of AF2-1DA produced by finishing and roughing EDM conditions are shown in Figure 111. The recast layer normally associated with EDM processing is evident on both samples. The layer is somewhat thicker on the sample cut under roughing conditions, Figure 111 (b), because of the higher current density, hence, thicker layer of molten metal developed during this mode of operation.

Undoubtedly the presence of the recast layer which is hard, brittle, and prone to cracking is the most significant feature in determining the surface integrity behavior of EDM surfaces. There was no evidence of microhardness change in the base metal as a result of whatever surface heating may have been involved in the processing. It is presumed that the recast layer was considerably harder than the base metal. On this particular group, however, it was not thick enough to be accurately measured by the standard microhardness techniques.

The condition used to produce the surfaces illustrated in Figure 111 are summarized in Table VIII.

Residual Stress

Residual stress profiles measured in AF2-1DA as a result of EDM processing are shown in Figure 112. In both cases, gentle EDM resulted in peak tensile stresses of 150 ksi. Abusive EDM exhibited a peak tensile stress of 175 ksi. Within the limits of experimental error, these test results can be considered as equivalent. While shallow tensile stresses are typical of nickel alloys when finished by EDM, the levels of stress exhibited by AF2-1DA are considerably higher than that found in other materials. In the case of AF95, for example, peak stress was approximately 120 ksi. In the case of Inconel 718 as evaluated in a previous effort, the peak stresses associated with finishing and roughing EDM ranged from 70 to 100 ksi in tension. It would appear logical to conclude, therefore, that AF 95, while behaving like other nickel alloys insofar as surface integrity response is concerned has a somewhat higher degree of sensitivity to the surface variables.

6.9.2 EDM - AF2-1DA, 46 R_c (continued)

High Cycle Fatigue Strength

The fatigue strength of AF2-1DA as a result of finishing and roughing EDM was determined to be 30 and 25 ksi, respectively as shown in Figure 113. This shows a marked depression below the value of 70 ksi exhibited for gentle grinding. In this respect, however, the behavior is about like that of other nickel alloys that have been studied. A summary of the fatigue data is contained in Table XXIV.

(a) Finishing Conditions
Surface Finish: 75 AA

(b) Roughing Conditions
Surface Finish: 170 AA

EDM applied to this alloy shows the usual recast layer adherent to the surface. Microhardness data showed a slight softening of approximately one R_c point at the .001 in. level beneath the surface. There are no visible surface alterations or indications of a heat affected zone. The presence of the recast surface layer is undoubtedly the most important feature in influencing the surface integrity of this alloy/metal removal combination. Indicated hardness data are R_c values converted from Knoop microhardness measurements. Surface finish measurements are averages of readings made on all specimens from each group.

Magnification: 1000X

Figure 111
SURFACE CHARACTERISTICS OF AF2-1DA (SOLUTION TREATED AND AGED, 46 R_c)
PRODUCED BY EDM

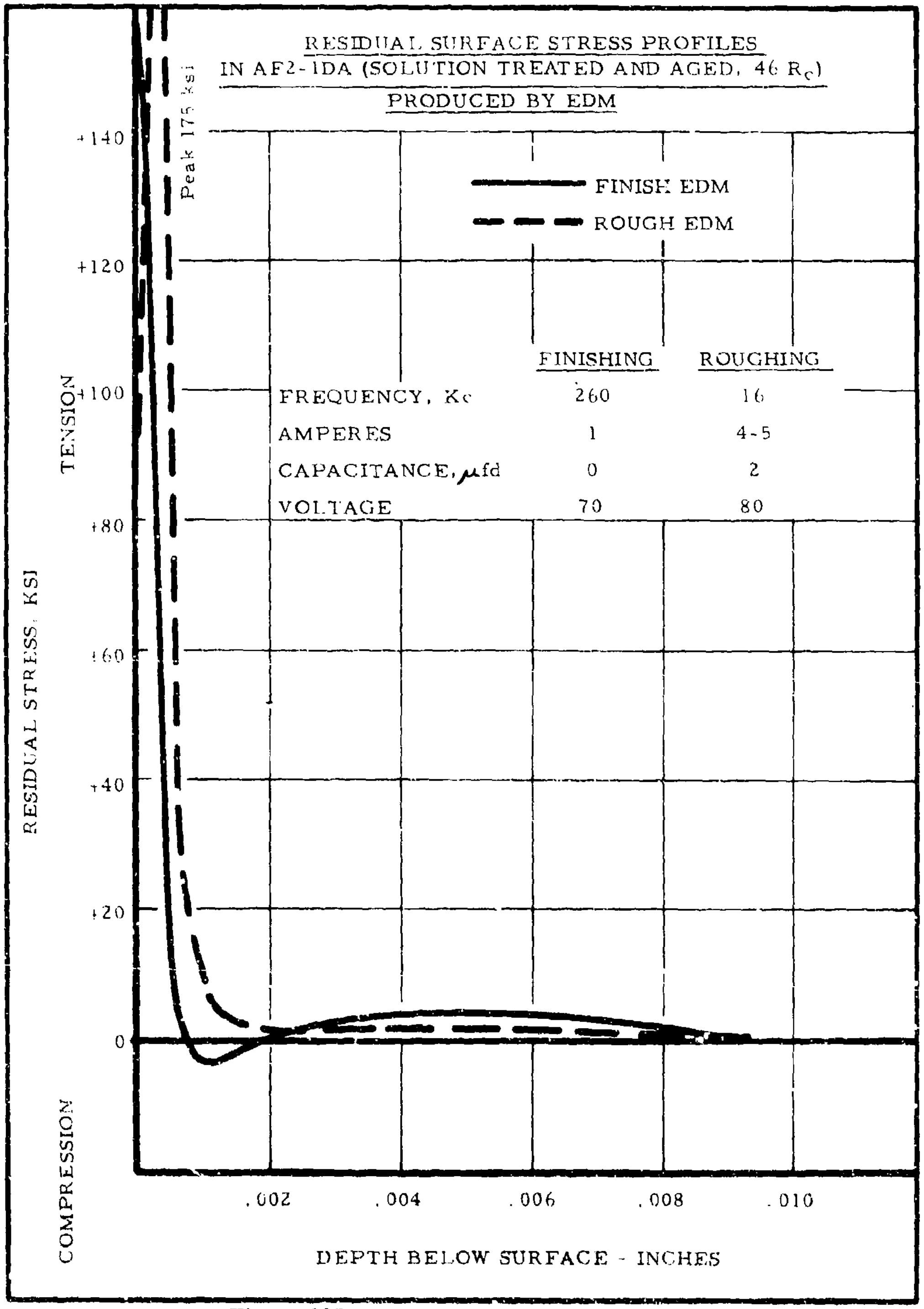


Figure 112
RESIDUAL STRESS IN AF2-1DA:
EDM

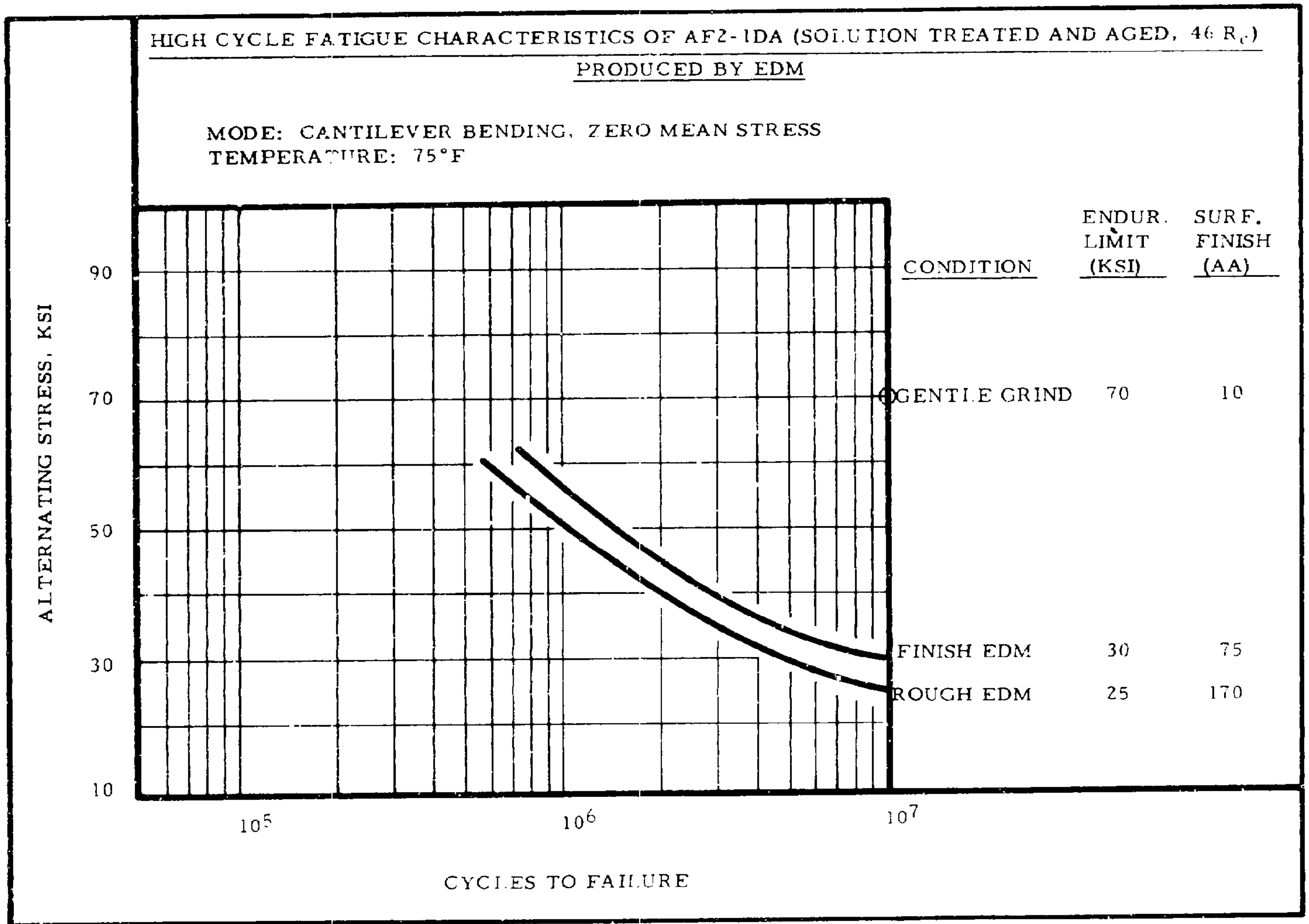


Figure 113
HIGH CYCLE FATIGUE OF AF2-IDA:
EDM

6.9.3 ECM - AF2-1DA, STA, 46 R_c

Metallography

Photomicrographs of surfaces of this alloy finished by ECM are shown in Figure 114. There is no evidence of plastic deformation or localized heating as would be indicated by an alteration of the surface structure. Microhardness data indicated a slight surface softening as shown in this figure. This behavior is typical of that exhibited by most materials when processed by ECM.

The only apparent differences between these surfaces is the microscopic difference in roughness in that the matrix of the alloy was attacked somewhat more rapidly than the second phase present under the standard and off-standard conditions. Off-standard processing also resulted in a somewhat rougher surface as measured on a macro scale by the standard surface finish instrumentation.

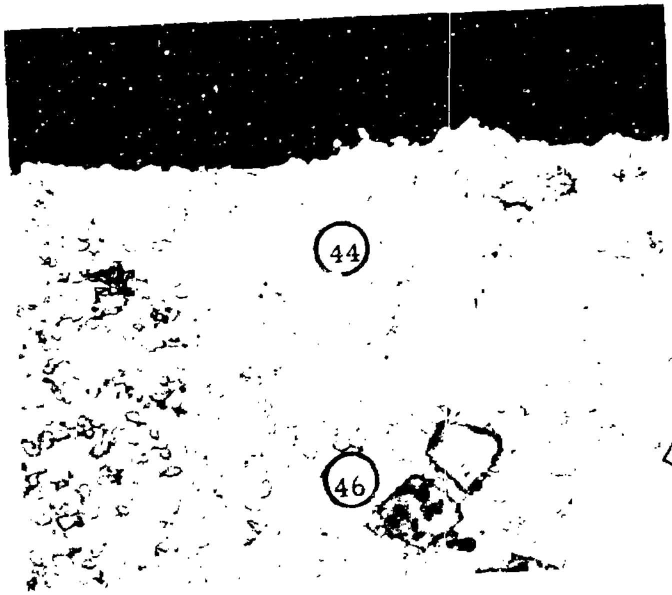
Residual Stress

Residual stress profiles determined for this alloy are shown in Figure 115. Normally ECM processing shows only a slight indication of a surface stress shift and without a significant peak or trend. In the case of ECM, both standard and off-standard conditions exhibited peak residual compression in the surface. These stresses were very shallow, however, and at the relatively low 20 ksi. This condition, since it does produce a residual compressive stress, would not be considered potentially dangerous to the surface integrity of the alloy.

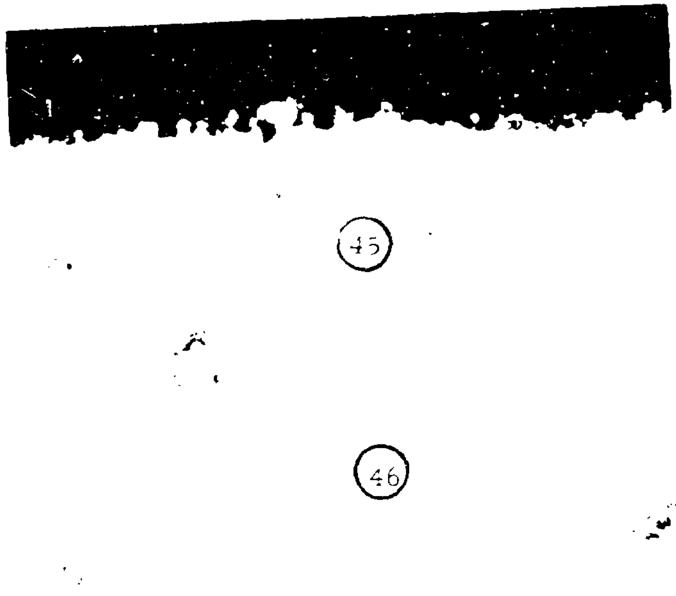
High Cycle Fatigue Strength

The high cycle fatigue behavior of AF2-1DA as a result of ECM processing is shown in Figure 116. A slight difference in fatigue strength is evidenced, in that the endurance limits associated with standard versus off-standard conditions were 65 versus 55 ksi.

A complete summary of the fatigue data on this alloy is contained in Table XXIV.



(a) Standard Conditions
Surface Finish: 30 AA



(b) Off-Standard Conditions
Surface Finish: 60 AA

These structures are typical of those exhibited by nickel-base alloys when finished by ECM. Evidence of plastic deformation or localized overheating at the surface is completely absent. Microhardness data indicate the typical softening to the extent of one to two points R_c at a depth of .001 in. beneath the surface. The only significant difference between them is the slight difference in microscopic roughness, the surface produced by the off-standard conditions being the rougher. Indicated hardness data are R_c values converted from Knoop microhardness measurements. Surface finish measurements are averages of readings made on all specimens from each group.

Magnification: 1000X

Figure 114
SURFACE CHARACTERISTICS OF AF2-1DA (SOLUTION TREATED AND AGED, 46 R_c)
PRODUCED BY ECM

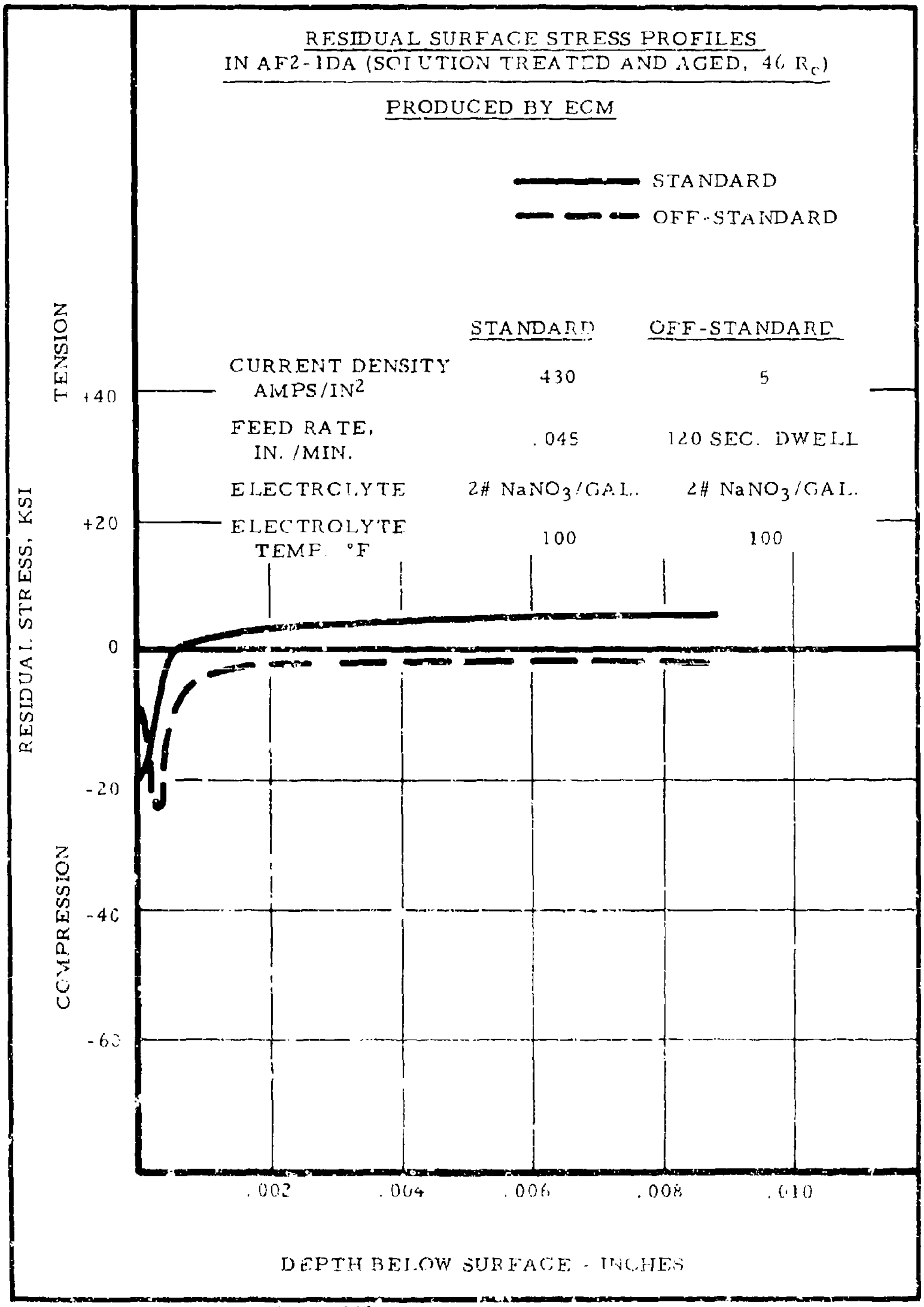


Figure 115
RESIDUAL STRESS IN AF2-1DA:
ECM

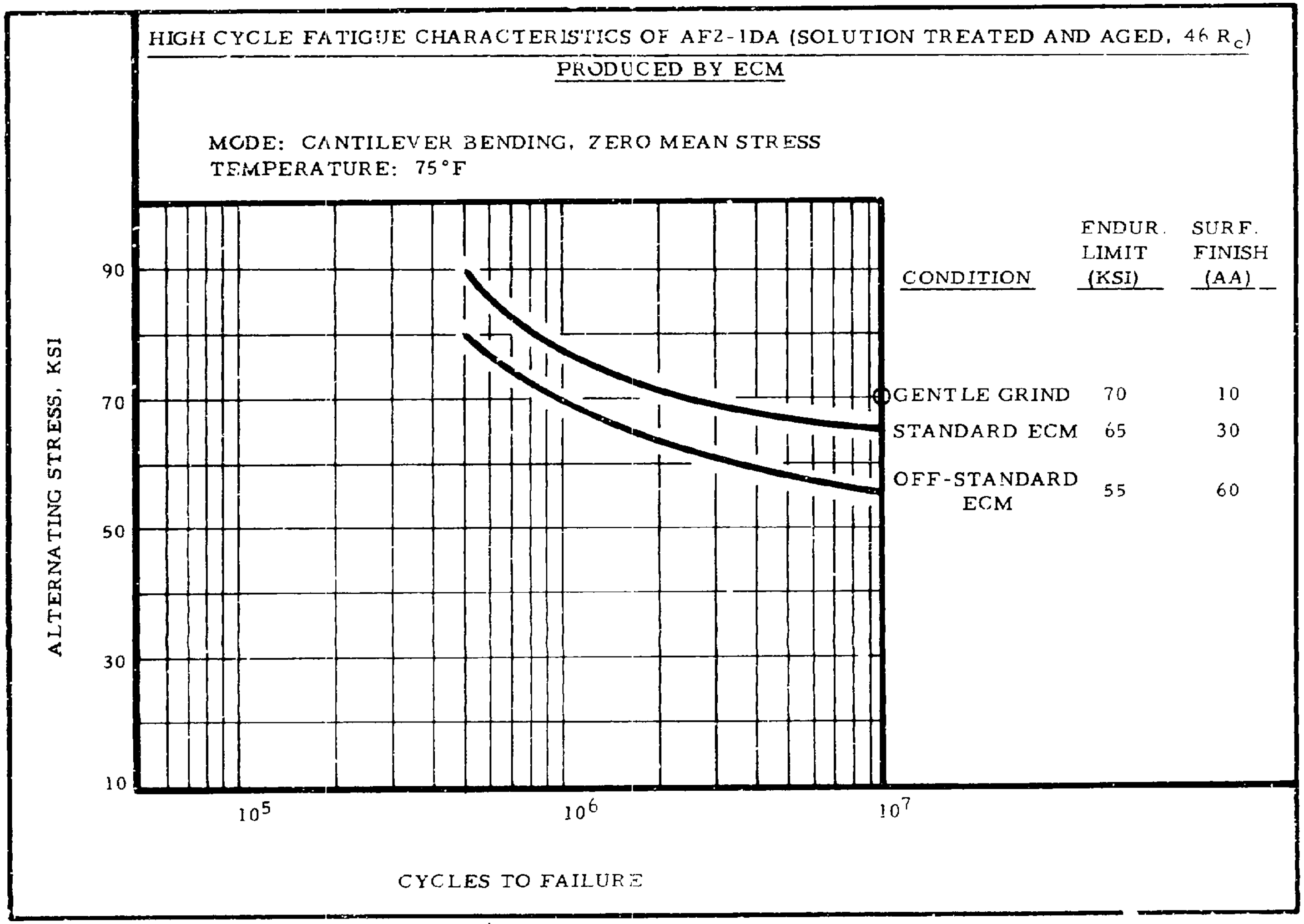


Figure 116
HIGH CYCLE FATIGUE OF AF2-1DA:
ECM

6.10 Rene' 80, Solution Treated and Aged, 40 R_C

The bar graphs shown in Figure 117 indicate the fatigue behavior of Rene' 80 as a result of a variety of surface conditions. Most significant of the variations is again the range of high cycle fatigue strengths associated with variations in grinding. Endurance limits associated with gentle, conventional, and abusive conditions were determined to be 42, 18, and 16 ksi, respectively. This alloy is slightly lower in strength (at room temperature) than the other nickel alloys covered in this report. Consequently, the range of differences in fatigue strength is less than for the other materials, but is nevertheless, very significant in determining alloy behavior.

EDM and ECM also exhibited endurance limits characteristic of the process, 26 and 28 ksi, respectively, as shown in Figure 117. Neither of these processes, however, indicated a sensitivity to metal removal parameters over the ranges studied.

Considering the widespread use of this alloy and other cast nickel base alloys in its class for turbine blading materials, particular interest was displayed in low cycle fatigue behavior as influenced by surface variables at a typical service temperature. As may be seen in Figure 117, the Rene' alloy was relatively insensitive at 1400°F to both grinding and EDM variations within the range studied. Shot peening, however, did have the effect of producing a small increase in fatigue strength. Comparing the minimum stress for a 20,000 cycle life of 45 ksi associated with abusive grinding to the best strength of 66 ksi associated with ECM plus peening, it is evident that there is need for some attention to the finishing of components made from these materials when low cycle fatigue limitations are important. The range in performance of the alloy, however, is less affected under these conditions than in the high cycle fatigue region.

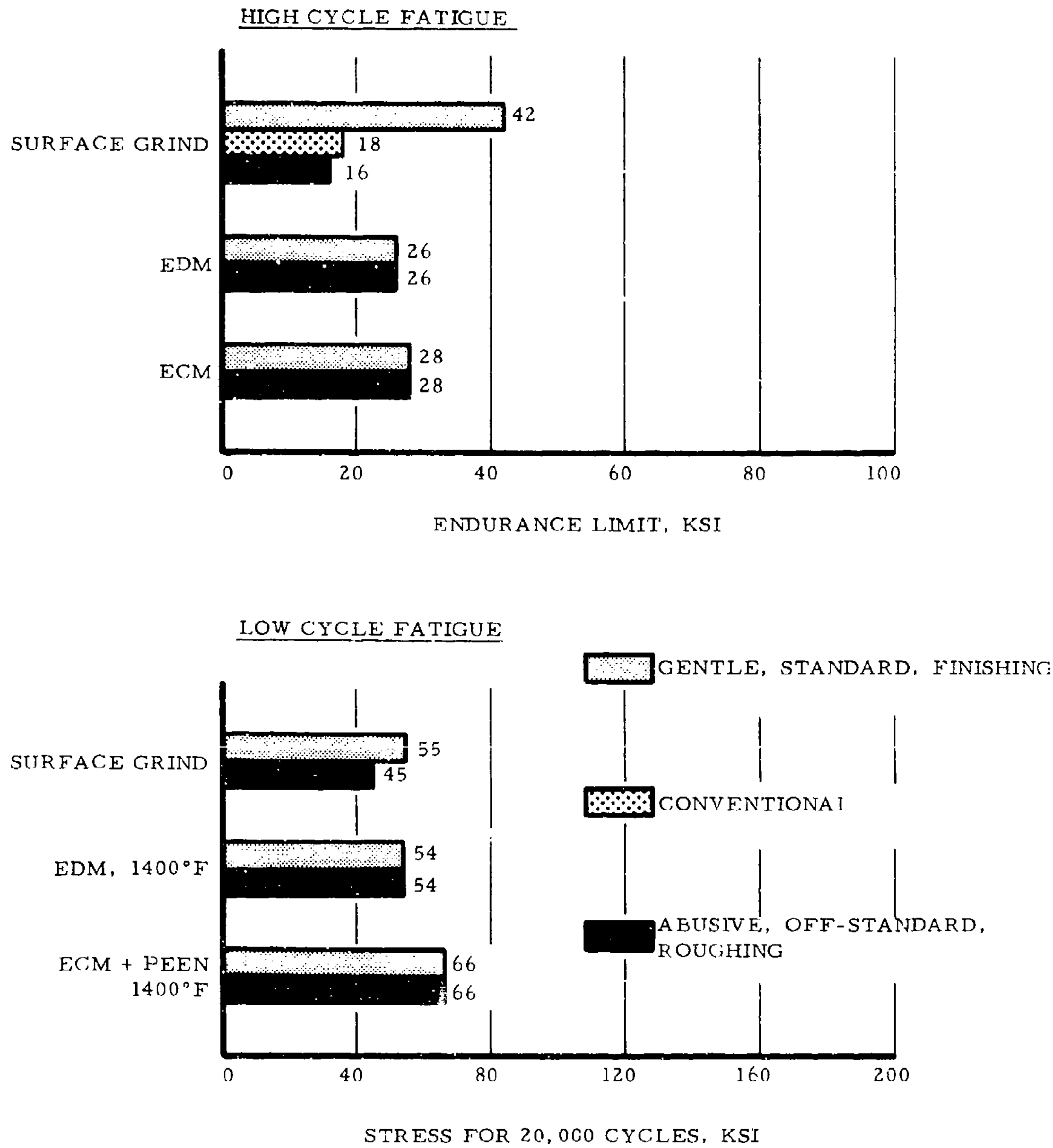


Figure 117
SUMMARY OF FATIGUE BEHAVIOR
OF RENE' 80 (SOLUTION TREATED AND AGED, 40 R_c)

6.10.1 Surface Grinding - Rene' 80, STA, 40 R_c

Metallography

Photomicrographs of the surface structures exhibited for ground samples of Rene' 80 are shown in Figure 118. Grinding conditions used to produce these samples are summarized in Table II.

All samples are free of visible surface alterations such as plastically deformed layers or structural changes. The surfaces tend to become slightly rougher as the grinding severity is increased. This is verified both visually and also by the surface finish measurements shown in Figure 118.

A slight microhardness increase was observed on all three ground samples. This behavior has been sometimes seen as a result of conventional and abusive grinding, but has not been previously observed as a result of gentle grinding conditions. The effect must be related to localized heating produced during grinding, although a specific explanation is not currently available.

Residual Stress

Residual stress profiles attributable to gentle, conventional, and abusive grinding are indicated in Figure 119. Gentle grinding resulted in a peak compressive stress of approximately 70 ksi. Conventional and abusive grinding resulted in peak tensile stresses of 115 and 190 ksi, respectively. This stress distribution is typical of that of other nickel base alloys finished by grinding.

High Cycle Fatigue Strength

High cycle fatigue strengths due to grinding variables are shown in Figure 120. Note that the endurance limits associated with gentle, conventional, and abusive grinding are 42, 18, and 16 ksi, respectively. This behavior, namely, that conventional and abusive grinding caused marked depressions in fatigue strength as compared to gentle grinding is typical of that of other nickel alloys that have been investigated. In the case of Rene' 80, the

6.10.1 Surface Grinding - Rene' 80, STA, 40 R_C (continued)

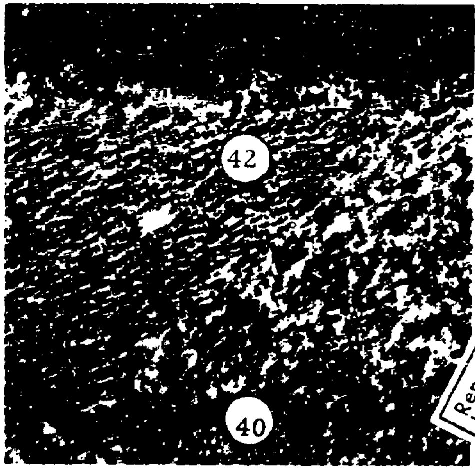
High Cycle Fatigue Strength (continued)

percentage of change, however, somewhat lower, probably associated with the lower inherent strength of this alloy at room temperature.

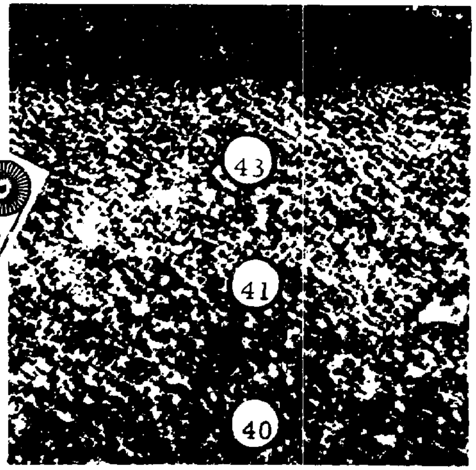
In comparison, endurance limits due to gentle grinding of wrought Inconel 718, AF2-1DA, and AF 95 all ranged from 60 to 75 ksi, while Rene' 80 was at the 42 ksi level. Considering this same group of materials following abusive grinding, however, the endurance limits for the wrought alloys fell in the range of 20 to 26 ksi as compared to 16 ksi for Rene' 80. While the percentage change in fatigue in Rene' 80 is somewhat less than that observed in these other nickel base alloys, it is still necessary to closely control surface grinding on this alloy whenever surface integrity conditions are important.

Low Cycle Fatigue Strength

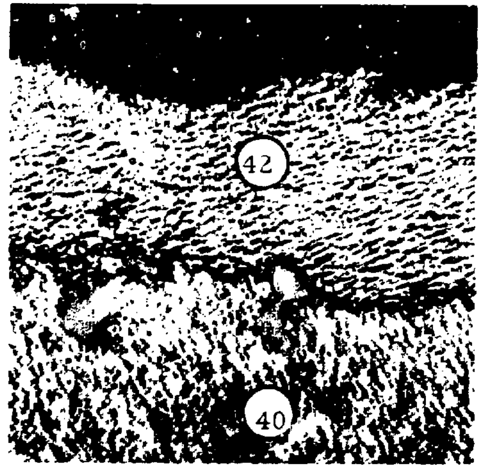
The low cycle fatigue response of Rene' 80 at 1400° F as a result of gentle versus abusive grinding is shown in Figure 121. In comparing this data at the 20,000 cycle life level, it may be seen that the fatigue strengths due to gentle versus abusive grinding are 55 versus 45 ksi. In another way of comparing behavior, it could be said that at the stress level of 55 ksi which produced a 20,000 cycle life due to gentle grinding, the cyclic life would be reduced to about 6,000 cycles in the event that abusive grinding were introduced. While normal design procedures would compare the 55 to the 45 ksi values, the potential for shortening of design life by abusive grinding at a pre-chosen stress level should not be overlooked. This data was obtained at 1400° F because of the need for surface integrity data under temperatures similar to those seen for this material in service.



(a) Gentle Grinding
Surface Finish:
Perpendicular to lay: 16 AA
Parallel to lay: 7 AA



(b) Conventional Grinding
Surface Finish:
Perpendicular to lay: 26 AA
Parallel to lay: 11 AA



(c) Abusive Grinding
Surface Finish:
Perpendicular to lay: [illegible] AA
Parallel to lay: 1[illegible] AA

Photomicrographs of Rene' 80 subjected to variations in grinding parameters are shown above. Typical of nickel alloys, and particularly the cast varieties, these photomicrographs show no visible effect resulting from localized surface heating which occurred during grinding. A slight roughness increase is noted for the abusively ground sample. Microhardness data indicate a slight surface hardening of all samples at depths as great as .002 in. This may be due to an accelerated aging effect from the surface heating although this has not been established. No plastic deformation is evident in any of the samples. Indicated hardness data are R_c values converted from Knoop microhardness measurements. Surface finish measurements are averages of readings made on all specimens from each group.

Magnification: 1000X

ORIENTATION: LONGITUDINAL GRIND. SURFACE SECTIONS PERPENDICULAR TO GRINDING LAY.

Figure 118
SURFACE CHARACTERISTICS OF RENE' 80 (SOLUTION TREATED AND AGED, 40 R[illegible]
PRODUCED BY SURFACE GRINDING

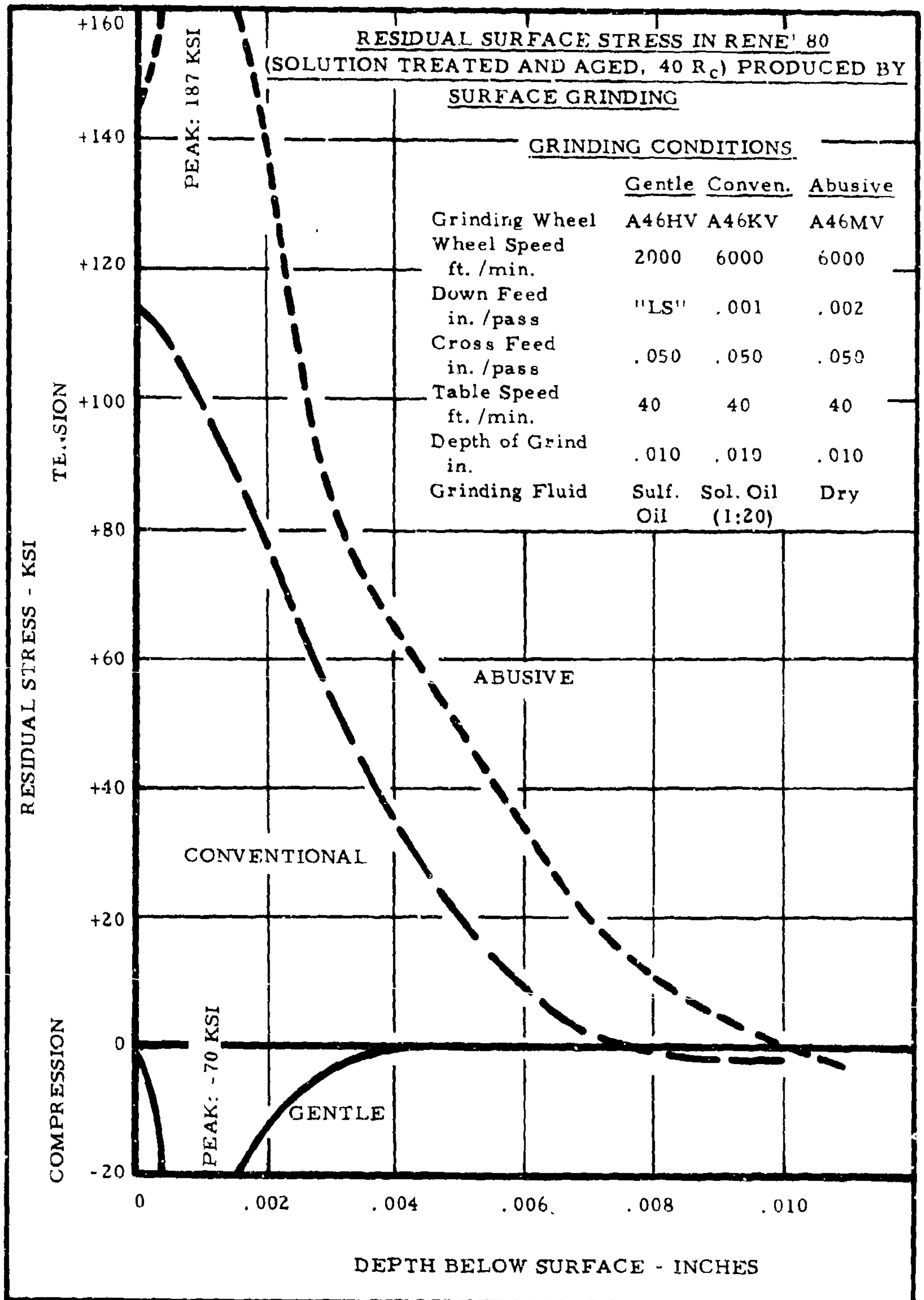


Figure 119
RESIDUAL STRESS IN RENE' 80:
SURFACE GRINDING

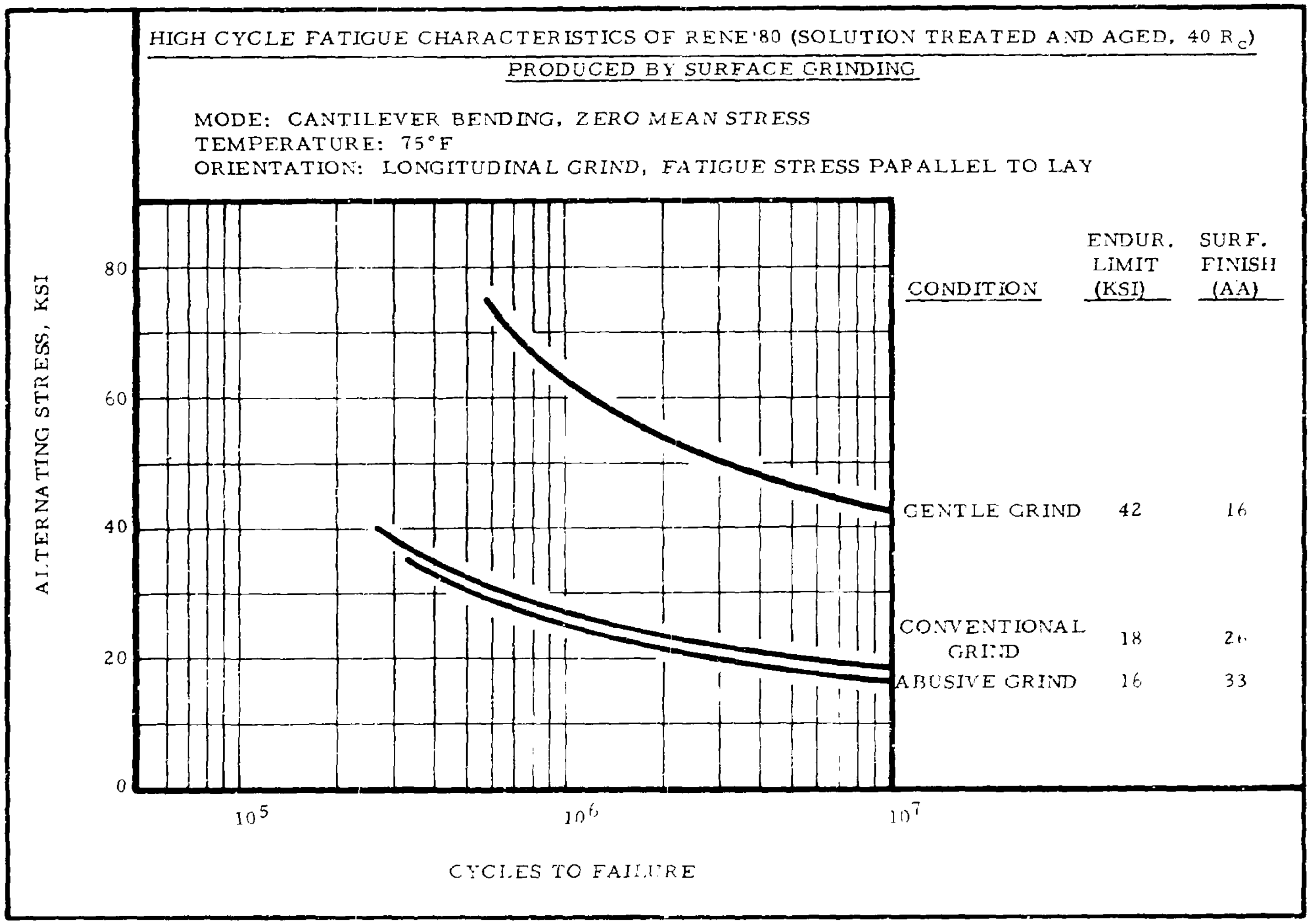


Figure 120
HIGH CYCLE FATIGUE OF RENE' 80
SURFACE GRINDING

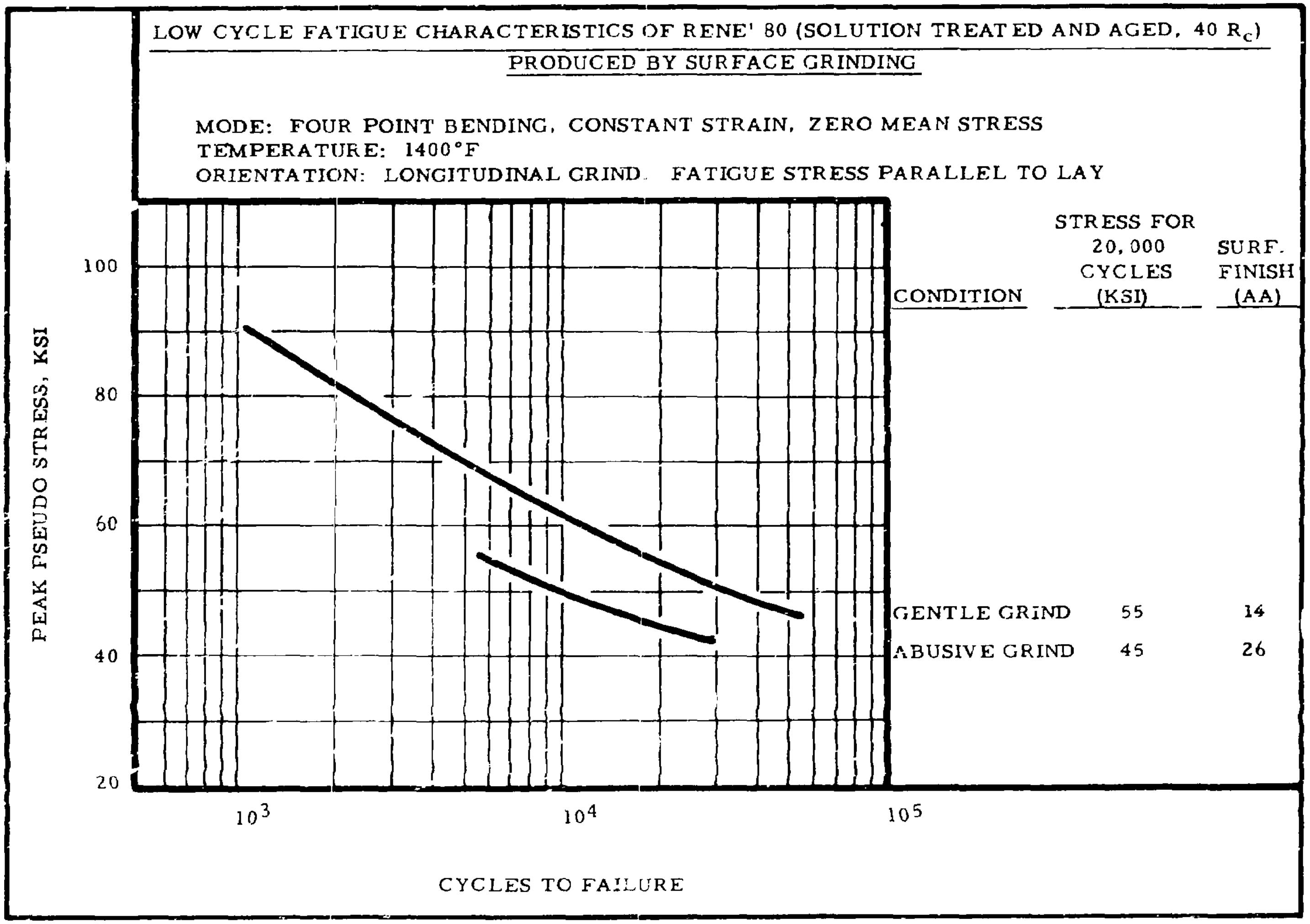


Figure 121
LOW CYCLE FATIGUE OF RENE' 80:
SURFACE GRINDING

6.10.2 EDM - Rene' 80, STA, 40 R_c

Metallography

Photomicrographs illustrating surfaces of Rene' 80 as a result of finishing and roughing EDM are shown in Figure 122. The recast layers present are typical, although somewhat thicker than those normally found on nickel alloys under these particular EDM parameters. The EDM layer on the roughing sample was thick enough to permit hardness measurements, it was found to be approximately 50 R_c, as compared to the base hardness of 40 R_c. Slight surface softening of 1 to 2 points R_c was noted beneath the recast layer. This is also shown in Figure 122.

Residual Stress

Residual stress profiles on the surfaces of these samples are presented in Figure 123. Both finishing and roughing conditions produced high shallow stresses which are tensile in nature. The peak stress of 250 ksi is a value indicated for the finishing condition. While the specific level may be subject to experimental error, due to presence of recast layer, the direction and magnitude appears to be well defined. Shallow tensile residual stresses are almost always associated with EDM surfaces.

High Cycle Fatigue Strength

The room temperature high cycle fatigue strength of Rene' 80 finished by EDM under roughing and finishing conditions is shown in Figure 124. The fatigue response shows lack of sensitivity to EDM variables which is typical. Notice that this occurs in spite of the large difference in surface finish, 70 versus 150 AA also indicated in Figure 124. Individual test points are summarized in Table XXV.

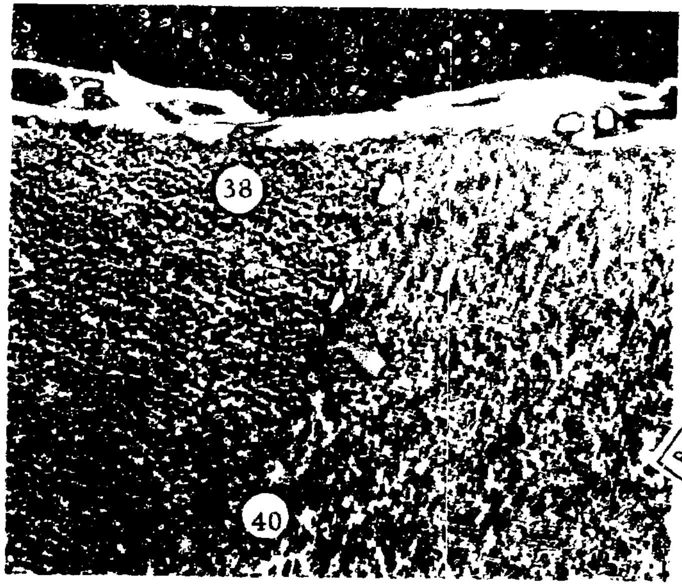
Low Cycle Fatigue Strength

A plot of the low cycle fatigue behavior of Rene' 80 at 1400° F finished by EDM is shown in Figure 125. As can also be verified by the individual test points contained in Table XXVI, the alloy appears completely insensitive to variations in EDM

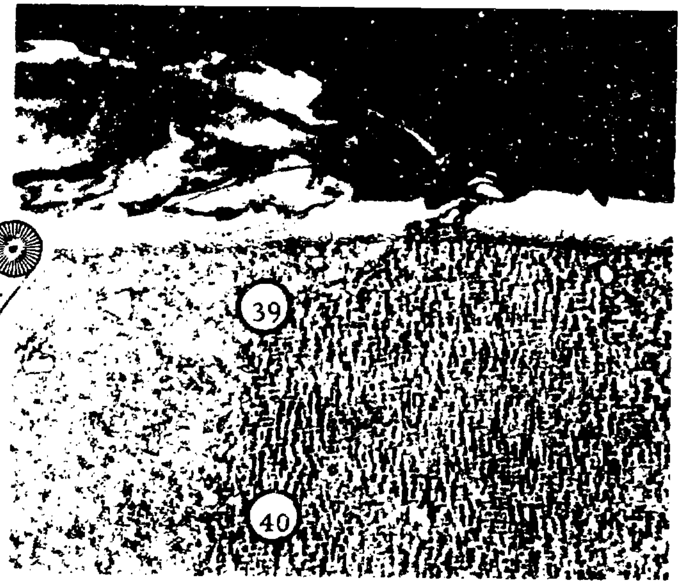
6.10.2 EDM - Rene' 80, STA, 40 R_c (continued)

Low Cycle Fatigue Strength (continued)

processing over the range covered. It is also significant to note that, at 1400°F, the stress to produce a 20,000 cycle life is essentially the same as that exhibited by gentle surface grinding (54 versus 55 ksi).



(a) *Finishing Conditions*
Surface Finish: 70 AA



(b) *Roughing Conditions*
Surface Finish: 150 AA

The above surface sections show the typical recast layer associated with EDM. The thickness of the layer, however, is somewhat heavier than has been found on other nickel-base alloys finished under equivalent conditions. In this case, the recast layer was thick enough to permit hardness measurement, determined as 50 R_c. Both samples exhibited a slight surface softening of one to two points R_c at a measurement of .001 in. beneath the recast layer. No plastic deformation is visible in either structure. Indicated hardness data are R_c values converted from Knoop microhardness measurements. Surface finish measurements are averages of readings made on all specimens from each group.

Magnification: 1000X

Figure 122
SURFACE CHARACTERISTICS OF RENE' 80 (SOLUTION TREATED AND AGED, 40 R_c) PRODUCED BY EDM

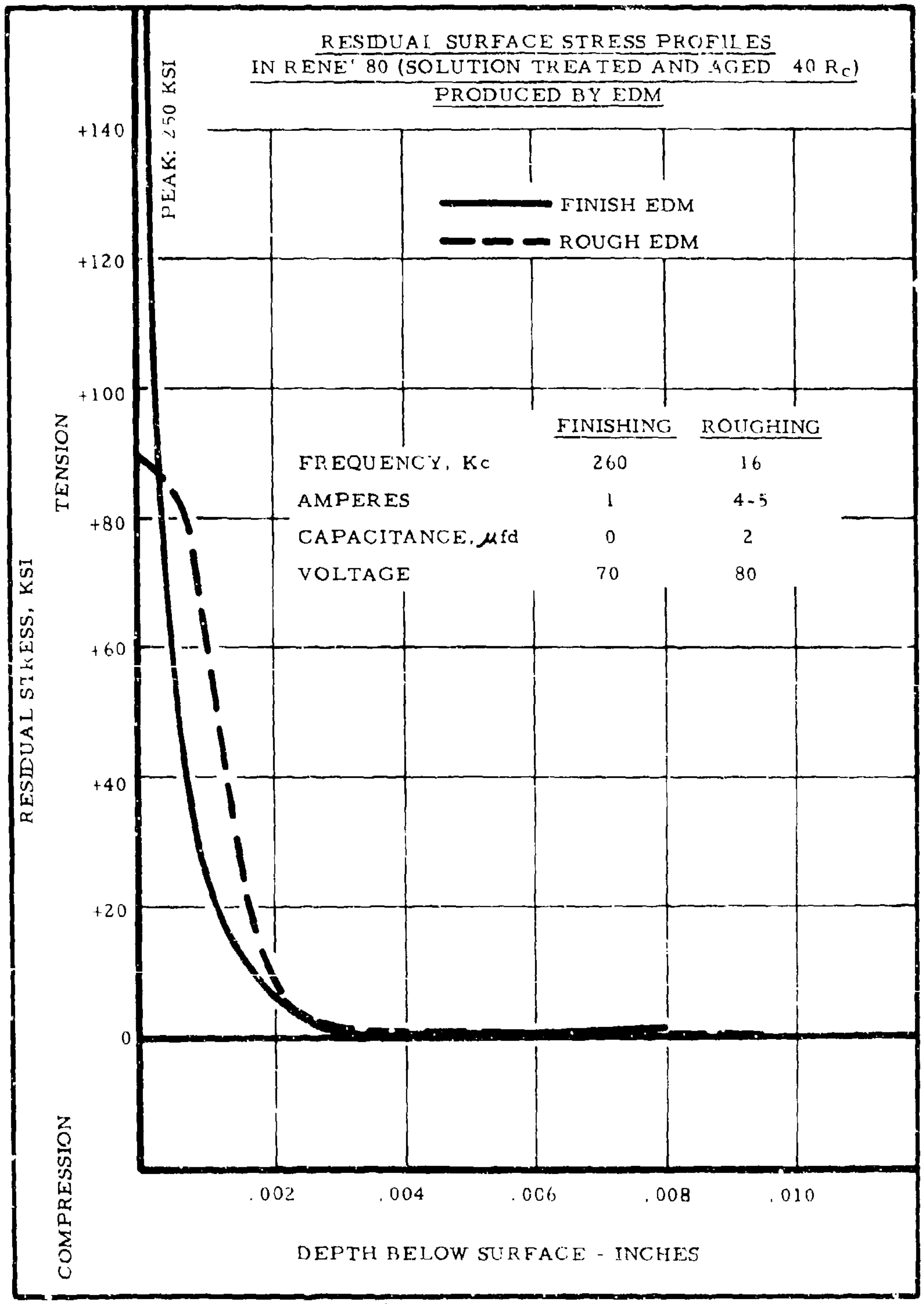


Figure 123
RESIDUAL STRESS IN RENE'80-
EDM

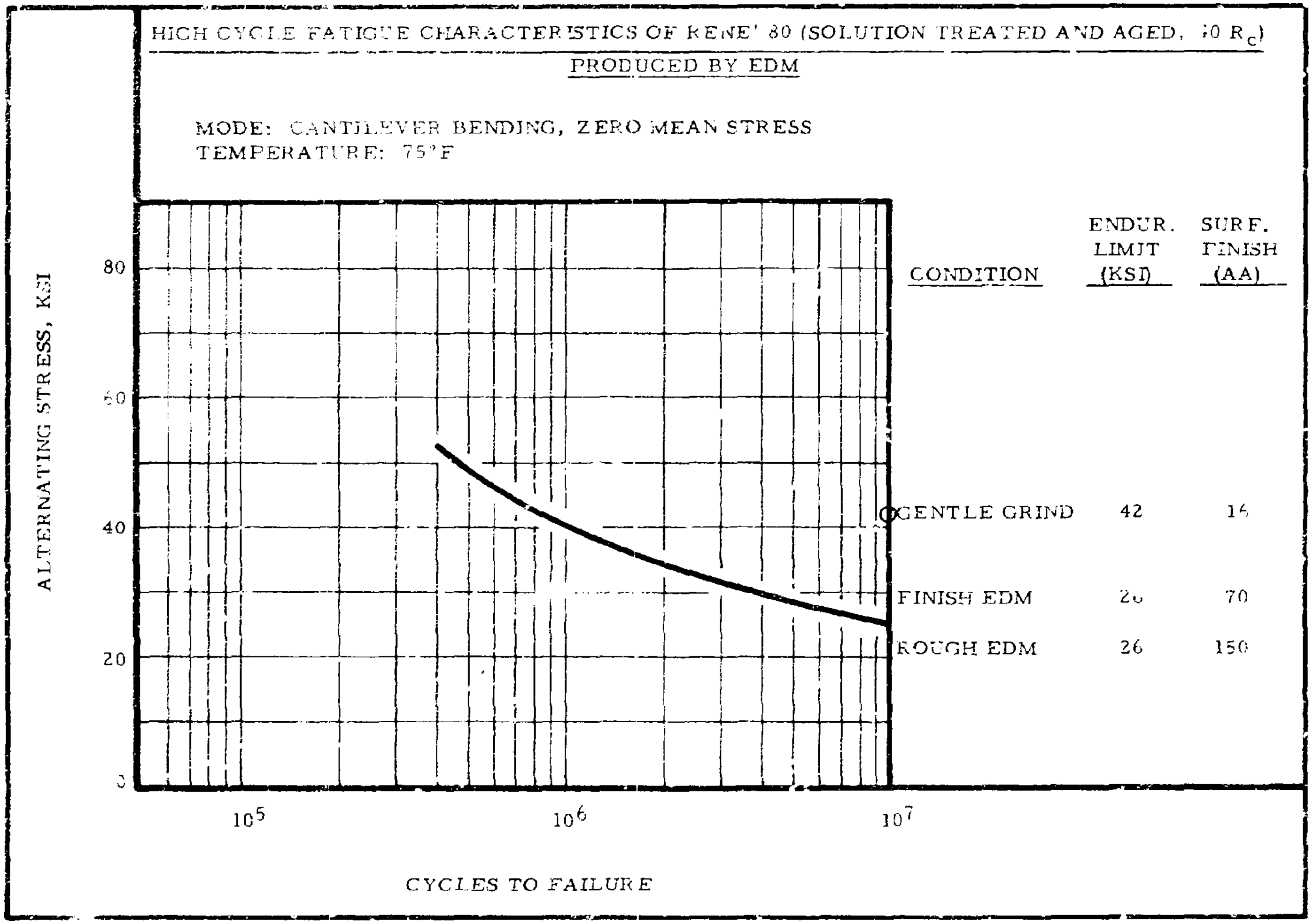
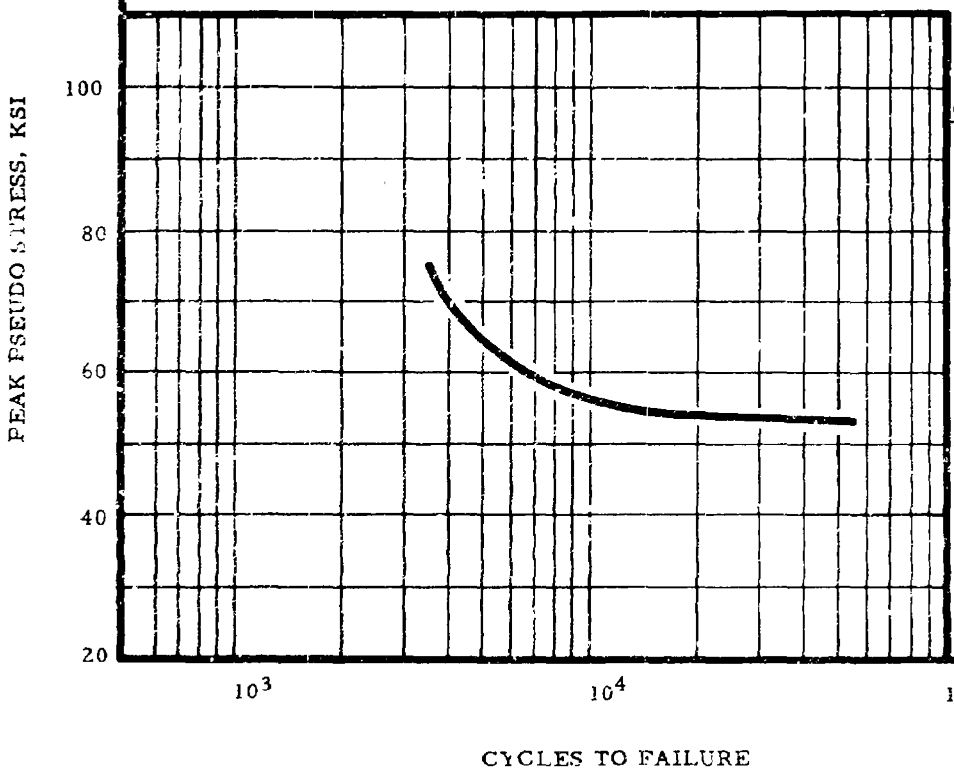


Figure 124
HIGH CYCLE FATIGUE OF RENE' 80:
EDM

LOW CYCLE FATIGUE CHARACTERISTICS OF RENE' 80 (SOLUTION TREATED AND AGED, 40 R_c)
PRODUCED BY EDM

MODE: FOUR POINT BENDING, CONSTANT STRAIN, ZERO MEAN STRESS
TEMPERATURE: 1400°F



CONDITION	STRESS FOR 20,000 CYCLES (KSI)	SURF. FINISH (AA)
FINISH EDM	54	67
ROUGH EDM	54	155

Figure 125
LOW CYCLE FATIGUE OF RENE' 80:
EDM

6.10.3 ECM - Rene' 80, STA, 40 R_c

Metallography

Surface microstructures resulting from ECM processing applied to Rene' 80 are shown in Figure 126. Both standard and off-standard conditions exhibited the same type of structure, with the latter being inclined toward somewhat greater roughness. The ECM conditions used to produce these test cuts are summarized in Table IX.

These structures both show the smooth unaltered surface structure characteristic of the ECM process. Microstructural evidence of overheating and plastic deformation are completely lacking. The differential machining rate on the matrix and the secondary phase in the structure is typical of ECM. Notice in the case of the standard sample, Figure 126 (a), the protrusion of a large carbide. A more common effect produced by selective etching is the development of surface pockets as a result of undermining secondary phase particles. This probably accounts for the pocket shown in Figure 126 (b). Notice also the possibility of some intergranular cracking in the grain boundary which emanates from the pocket.

The most significant feature of these structures probably lies in the microhardness loss which is indicated in the figure. The standard sample shows a hardness loss of 5 points R_c at the .001" level and a somewhat greater loss although not indicated in the photomicrograph at the .0005" level. Off-standard ECM resulted in hardness losses of 7 points R_c at the .001" level. Readings as low as 29 R_c were measured .0005" from the surface of the sample shown in Figure 126 (b), although data at depths shallower than .001" are not generally reported in the illustrations. The surface softening phenomena has come to be associated with ECM. The extent of softening in Rene' 80, however, is generally greater than that which has been observed in other alloys under roughly equivalent processing conditions.

Residual Stress

Both types of ECM processing resulted in virtually stress free samples as indicated by Figure 127. This is typical of the behavior of alloys when finished by ECM.

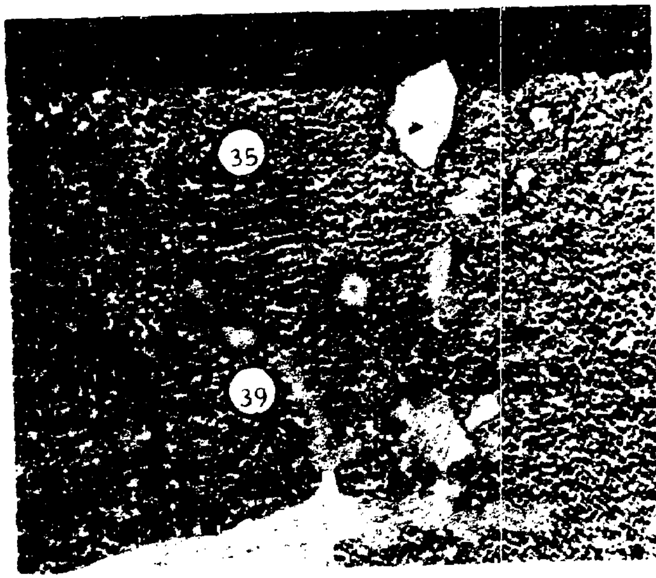
6.10.3 ECM - Rene' 80, STA, 40 R_c (continued)

High Cycle Fatigue Strength

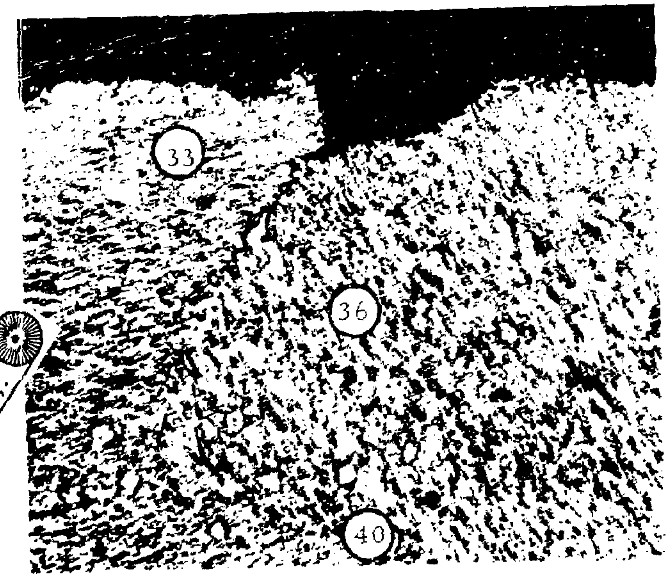
The high cycle fatigue behavior of Rene' 80 produced by ECM is shown in Figure 128. Note that both standard and off-standard conditions exhibited the identical endurance limit of 28 ksi, in spite of the difference in surface finish, 20 and 40 ksi. Again, this response to ECM parameters is typical, indicating a lack of surface integrity sensitivity to variations of the ECM process. These data are summarized in Table XXV.

Low Cycle Fatigue Strength

The low cycle fatigue strength of Rene' 80 finished by ECM and subsequent shot peening and measured at 1400°F is described by Figure 129. Similar to previously described behavior, standard versus off-standard parameters resulted in a single curve of fatigue behavior. After shot peening, by inference from other data, it may be presumed that an equivalent response due to the two different ECM methods would also be indicated before peening, had this data been obtained. The low cycle fatigue data on this alloy is summarized in Table XXVI.



(a) Standard Conditions
Surface Finish: 20 AA



(b) Off-Standard Conditions
Surface Finish: 40 AA

The above surfaces are typical of those produced by application of ECM to cast alloys. In particular, is the tendency toward differential rates of attack of the matrix as compared to the secondary phases. This effect is particularly clearer in Figure (a) where a carbide is protruding from the surface. Figure (b) indicated an area where a carbide has been cut from the surface with the suggestion of a grain boundary crack developing from the void. Significant surface softening of five to seven points R_c was measured on these samples. Indicated hardness data are R_c values converted from Knoop microhardness measurements. Surface finish measurements are averages of readings made on all specimens from each group.

Magnification: 1000X

Figure 126
SURFACE CHARACTERISTICS OF RENE' 80 (SOLUTION TREATED AND AGED, 40 R_c)
PRODUCED BY ECM

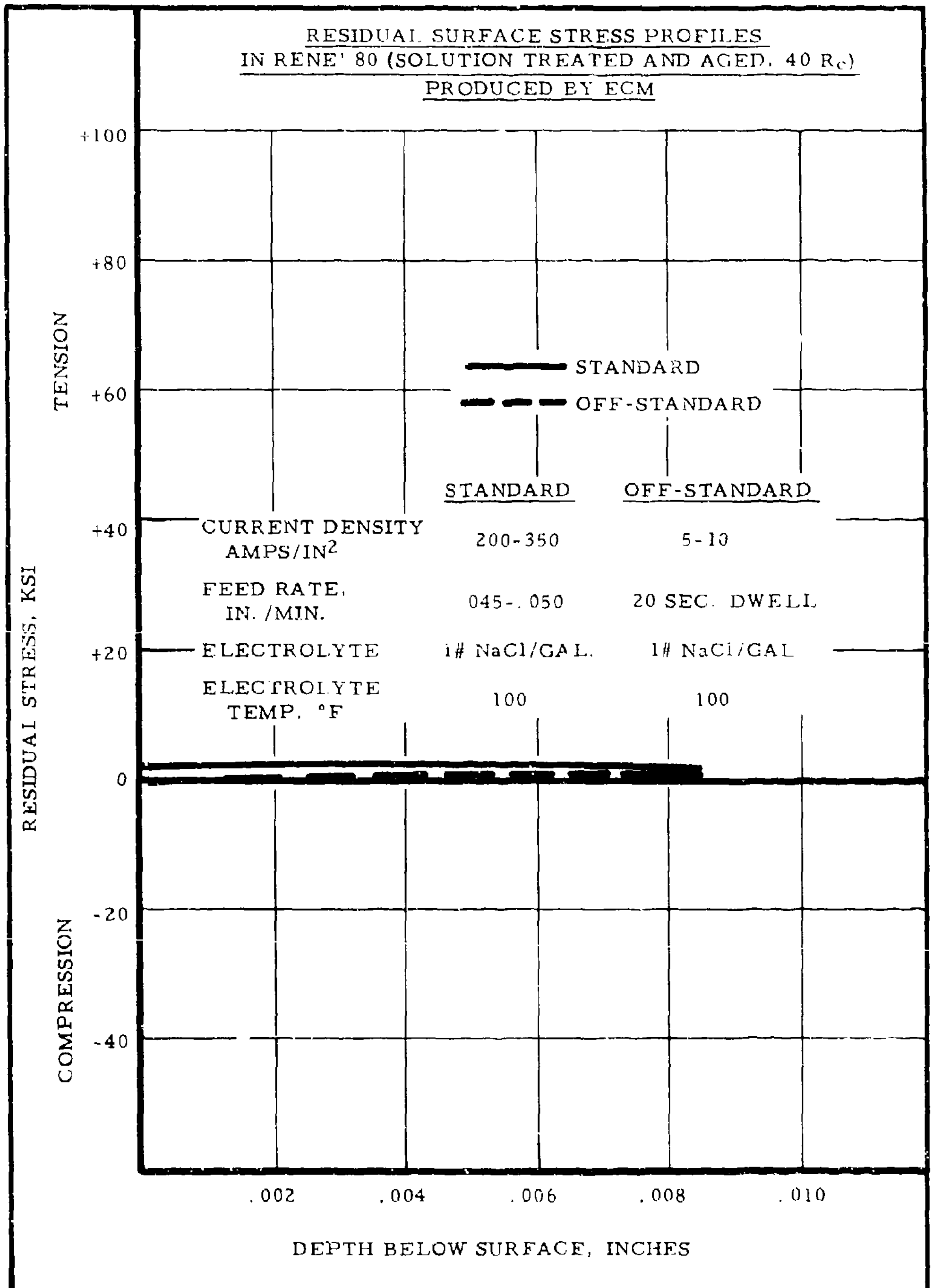


Figure 127
RESIDUAL STRESS IN RENE' 80:
ECM

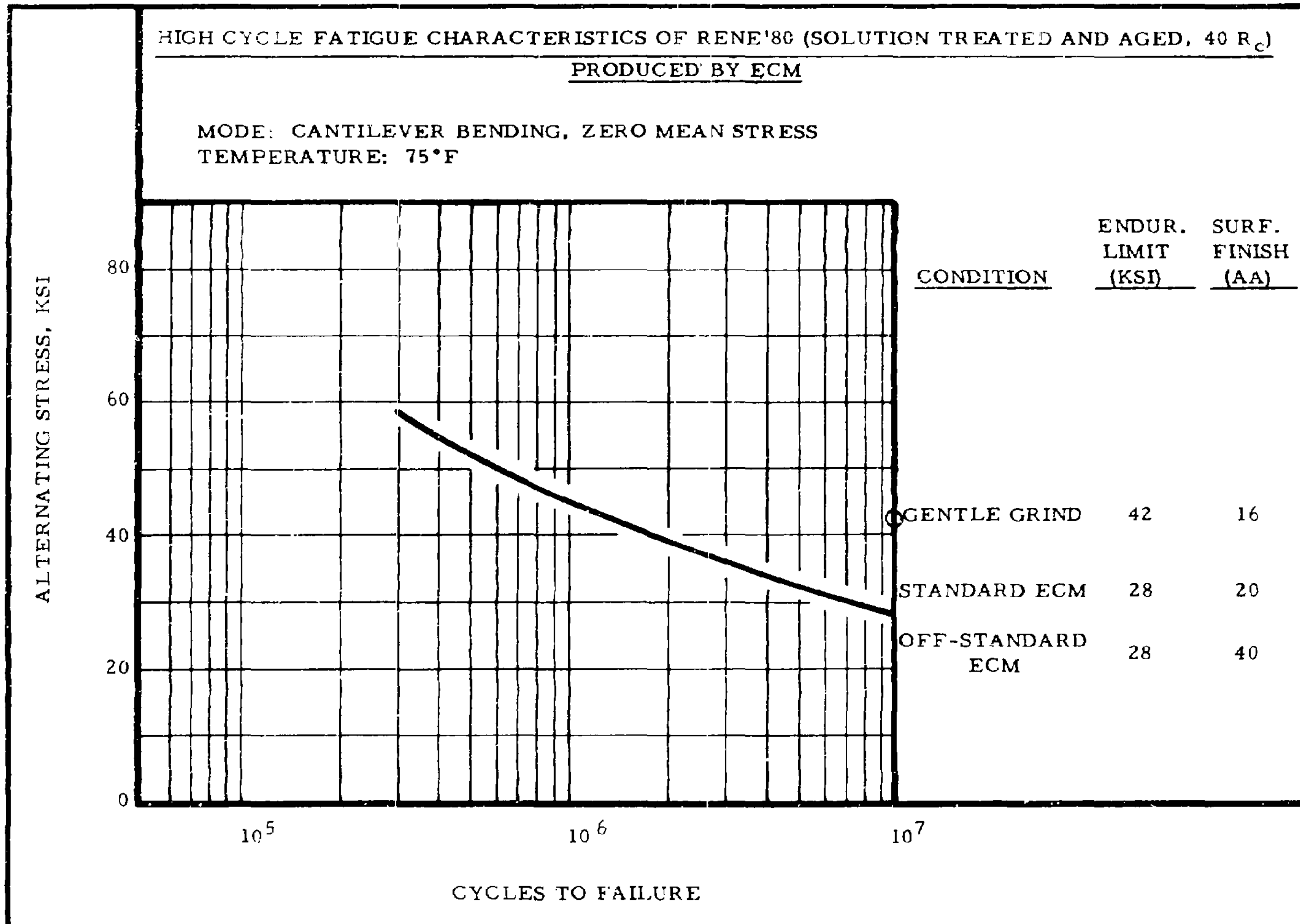
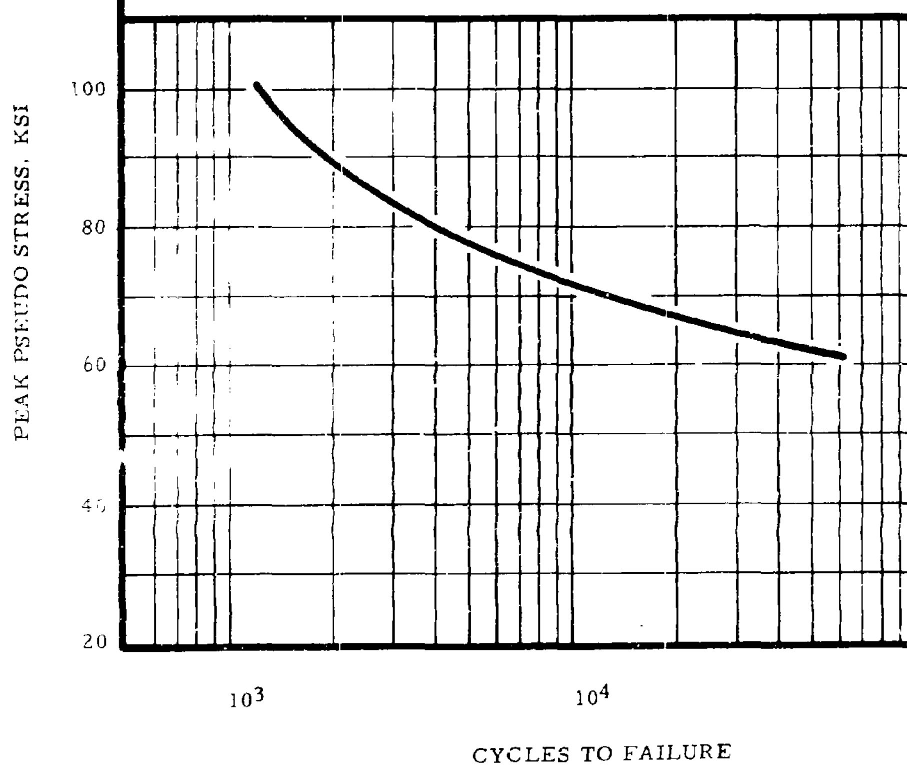


Figure 128
HIGH CYCLE FATIGUE OF RENE' 80:
ECM

LOW CYCLE FATIGUE CHARACTERISTICS OF RENE' 80 (SOLUTION TREATED AND AGED, 40 R_c)
PRODUCED BY ECM PLUS SHOT PEENING

MODE: FOUR POINT BENDING, CONSTANT STRAIN, ZERO MEAN STRESS
TEMPERATURE: 1400°F



CONDITION	STRESS FOR 20,000 CYCLES (KSI)	SURF. FINISH (AA)
STANDARD ECM + PEEN	66	14
OFF-STANDARD ECM + PEEN	66	48

Figure 129
LOW CYCLE FATIGUE OF RENE' 80:
ECM - SHOT PEENING

6.11 Surface Finish Study

A surface finish study has been developed specifically to explore the relation between the microinch finish of a machined surface and its characteristic fatigue strength. In preparing these samples, differences between the surfaces other than finish were intentionally kept as small as possible. One of the specific purposes of the study was to determine the sensitivity and suitability of microinch finish as an index of surface integrity. Surface finish studies were run as follows:

> Gentle and abusive grinding -- 4340 steel (quenched and tempered, 50 R_c)
>
> Gentle turning -- Inconel 718 (solution treated and aged, 44 R_c)
>
> Gentle end milling -- Ti-6Al-6V-2Sn (solution treated and aged, 42 R_c)

In preparing the test specimens, surface finish was varied widely, keeping all other factors as constant as possible. In all of these studies, gentle cutting was used as the base condition. Abusive cutting at a single surface finish level was used in some instances for comparison. Residual stress profiles were measured in each case. It was intended that these be about the same for each metal removal/alloy combination. Significant differences in residual stress within each group, should they occur, would add a bias to the test results and confuse the isolated effect of surface finish on fatigue strength.

A summary of the data obtained from this study is shown in Figure 130. In gentle longitudinal grinding, note that the fatigue strength varied from 117 to 100 ksi as surface finish was varied from 8 to 127 AA. In the transverse orientation with the lay of the surface perpendicular to the applied cyclic stress, the fatigue strength range increases to 120 to 85 ksi for a similar range of surface roughness. An inverse proportionally between finish and fatigue strength is therefore indicated for gentle grinding, with the sensitivity being higher when the stress is perpendicular to the grinding lay. Note, however,

6.11 Surface Finish Study (continued)

that the fatigue strength level associated with abusive grinding is significantly lower, 65 ksi; this condition shows no bias due to variation in surface finish.

End milling-end cutting of Ti-6Al-6V-2Sn shows no fatigue variation in fatigue behavior due to surface finish variation over the range studied. Finishes ranging from 13 to 125 AA all yielded an endurance limit of 82 ksi. All milling cuts were made with sharp tools under gentle cutting conditions.

Turning of Inconel 718 also shows no variation in fatigue response, regardless of cutting conditions. Gentle turning with sharp tools, performed as a facing operation, resulted in a uniform fatigue strength of 60 ksi, although finishes ranging from 25 to 118 AA were evaluated. Abusive turning with dull tooling, resulting in a finish of 76 AA also yielded a fatigue strength of 60 ksi. The data are also summarized in Figure 130.

Considering these relationships, it is evident that surface finish may not have as direct a role in influencing the fatigue behavior of materials as has been traditionally accepted. In sensitive situations such as grinding, factors other than finish seem predominant even though finish variations do exert an influence. In non-sensitive situations, perhaps needless attention and expense has been directed at improving the surface finish of components beyond nominal levels.

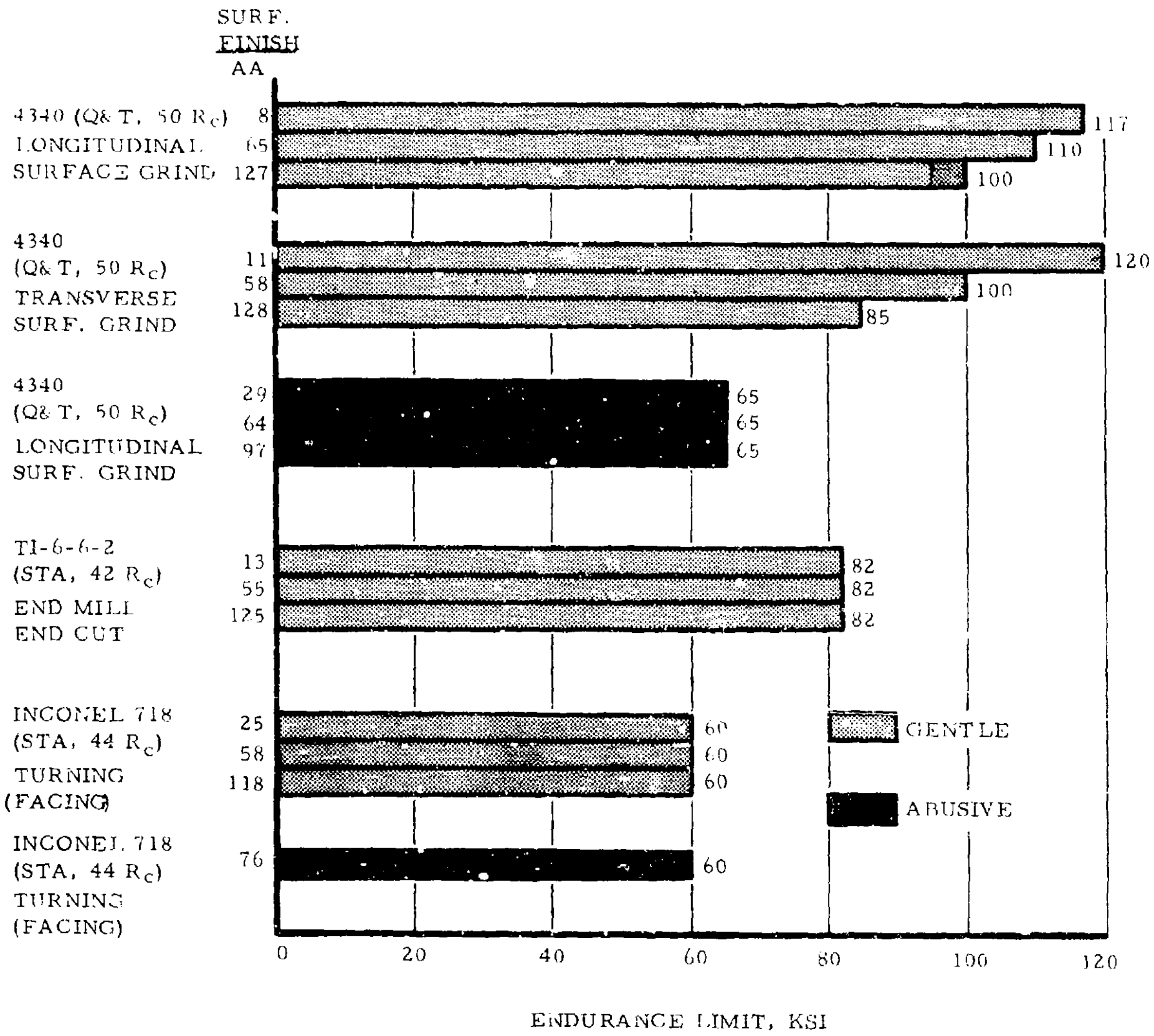


Figure 130
SUMMARY OF FATIGUE STRENGTHS - SURFACE FINISH STUDY

6.11.1 Surface Finish Study: Surface Grinding AISI 4340 Steel, Q & T, 50 R_c

Surface grinding studies were run on samples finished by both longitudinal and transverse grinding (see Figure 12). The same grinding conditions were used in both directions, hence the data contained in this report indicate the relationship of surface finish to the properties studied, both in terms of roughness and orientation.

Metallography

Photomicrographs summarizing the surface metallography observed in longitudinally ground samples under gentle conditions are shown in Figures 131 and 132. Figure 131 illustrates surfaces whose sections are perpendicular to the grinding lay, while Figure 132 illustrates surfaces whose sections are parallel to the grinding lay. As indicated in the section on specimen manufacturing, it was found that the most important variables in producing the range of surface finishes within a specific mode of grinding was the procedure used in dressing the wheel (Table X).

Figure 131 shows variations in surface microstructure associated with the obtained range in microinch finish, 8 to 127 AA. Microhardness measurements were made on several samples from each of the surface finish groups. No significant surface softening was found in any of the gently ground samples. In addition, no surface layers or microstructural alterations were observed. These findings are consistent with the previous observations made after low stress grinding. Surface finish measurements were taken on these samples both perpendicular and parallel to the lay. These data are summarized in Figure 132.

Figure 132, showing sections of these same surfaces parallel to the grinding lay, indicates the same characteristics with respect to microhardness, lack of plastic deformation, etc., as noted above. In Figure 132, however, some tendency to form laps and smears on the surface, which is parallel to the cutting action, can be observed.

6.11.1 Surface Finish Study: Surface Grinding AISI 4340 Steel, Q & T, 50 R_c (continued)

Metallography (continued)

Experimentation with abusive longitudinal grinding yielded specimens having maximum surface roughness ranging from 29 to 97 AA. Photomicrographs of cross sections of these surfaces are shown in Figure 133. Here again, the visual surface roughness approximates the measured value. In the case of the abusively ground surfaces, however, all specimens exhibited the characteristic layer of hard untempered martensite and an underlying overtempered zone. This has been previously found and reported on many occasions as a typical result of abusive grinding applied to a martensitic steel. On three groups of samples, the maximum martensite hardness was found to be approximately 62 R_c. The minimum hardness in the overtempered zones immediately beneath the martensite ranged from 42 to 46 R_c. All of the abusive samples showed non-uniform patches or streaks of untempered martensite on the surface. Maximum depth of untempered martensite observed was approximately .002 inches. In surface regions where untempered martensite was not formed, softened overtempered martensite was generally present. This can be understood by realizing that the surface heating in these softened areas was sufficient to cause the tempered or softening reaction, but not quite great enough to cause rehardening to occur.

Figures 134 and 135 show surfaces produced by transverse grinding under gentle conditions. Sections both perpendicular and parallel to the grinding lay are again illustrated. As can be seen by comparing Figure 131 with Figure 134 and Figure 132 with Figure 135, no distinction exists between the metallurgical conditions observed as a result of longitudinal versus transverse grinding. Nor were any expected since only the direction of grinding was changed (Figure 12). Slightly different surface finish readings were obtained, however, since the values reported were averages of the particular specimens within each group.

Residual Stress

Residual stress profiles obtained under gentle and abusive longitudinal grinding conditions are shown in Figures 136 and 137. Each curve illustrates the residual stress profiles

6.11.1 Surface Finish Study: Surface Grinding AISI 4340 Steel, Q & T, 50 R_c (continued)

Residual Stress (continued)

associated with the range of surface finishes studied. In longitudinal grinding, the data indicate residual stress in the direction parallel to the grinding lay. Note that the gently ground samples all exhibit shallow zones of residual compressive stress having a total affected depth of less than .002 inches. The best surface finish, 8 AA, however, indicates an extremely shallow but high level of residual tension in the surface.

All of the abusively ground samples exhibit high residual tensile stresses as shown in Figure 137. The total affected depth ranged from .008 to .012 inches. These residual stress profiles are typical of what has been previously observed under similar conditions.

Figure 138 shows residual stress profiles associated with gentle transverse grinding. In this situation, the residual stress is measured in a direction perpendicular to the grinding lay. The predominant characteristic of all of these curves is one of moderate residual compression. The medium and rough surfaces are very similar. The finest surface finish, however, shows extremely shallow, but high level compression in the direction perpendicular to the grinding lay (Figure 138).

This same type of surface finish shows extremely shallow but high level tension in the direction parallel to the grinding lay (Figure 136).

Fatigue Strength

S/N curves were run on eight specimens for each of the surface finish conditions described in Figures 131 through 135. The resulting data are summarized in Table XXVII. A summary of this information is shown graphically in Figures 139, 140, and 141.

6.11.1 Surface Finish Study: Surface Grinding AISI 4340 Steel, Q & T, 50 R_c (continued)

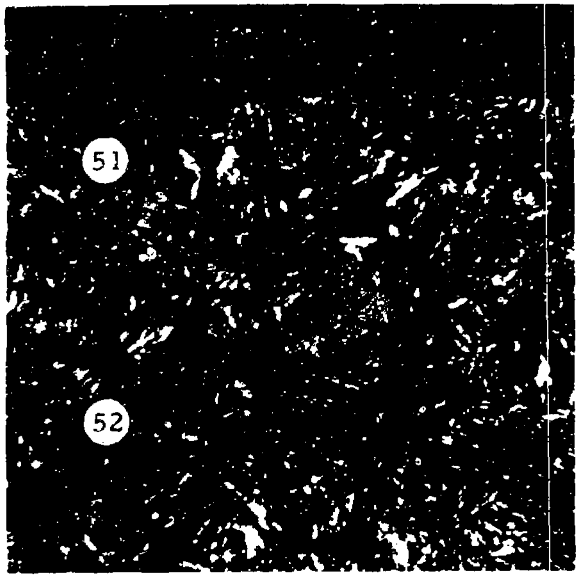
Fatigue Strength (continued)

Fatigue behavior of longitudinally ground samples having the grinding lay parallel to the principal fatigue stress is summarized in Figure 139. It will be noted that the samples which were ground by gentle techniques (which result in low surface stress) show a variation apparently due to surface finish. The samples with the best surface finish, averaging 8 AA, exhibit an endurance limit of 117 ksi. Gently ground samples having average surface finishes of 65 and 127 AA exhibit endurance limits of 110 and 100 ksi, respectively. In contrast, all of the abusively ground samples adhered rather closely to the single S/N curve shown in Figure 139 as representing the abusive conditions. Considering the relatively low scatter exhibited by three abusively ground samples, all three groups pointed rather clearly to an endurance limit in the vicinity of 65 ksi.

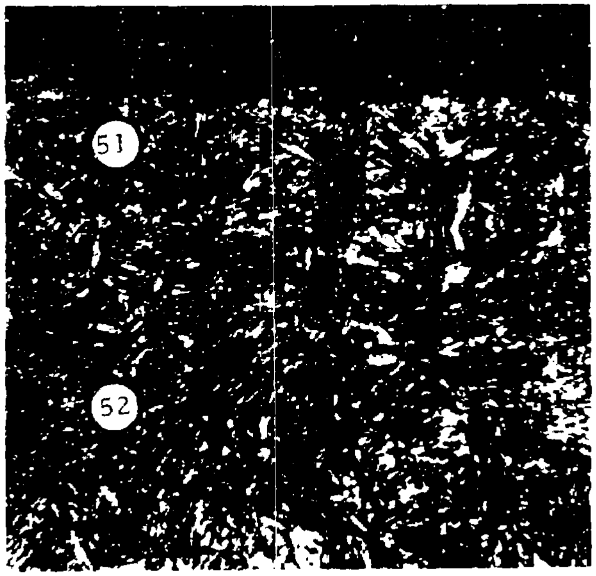
Fatigue data summarizing the effects of gentle transverse grinding in the range of 11 to 128 AA are shown in Figure 140. These data represent the effect of grinding lay perpendicular to the principal fatigue stress. The range in endurance limit, 120 down to 85 ksi, is somewhat greater than that associated with the grinding lay being parallel to the surface, 117 to 100 ksi. These ranges in fatigue strength are believed due to differences in surface finish.

For ease of comparison, the ranges obtained in both longitudinal and transverse gentle grinding on 4340 are graphed together in Figure 144. The total spread in endurance limit for gentle longitudinal grinding amounts to ± 7 percent of the average value. The total spread in endurance limit for transverse grinding (in which the fatigue stress is perpendicular to the lay) is ± 17 percent of the average value. It may be concluded, therefore, that surface finish does exert a measurable influence on fatigue strength of ground surfaces in the absence of other significant surface alterations. The effect appears to be more pronounced when the grinding lay is perpendicular to the fatigue stress.

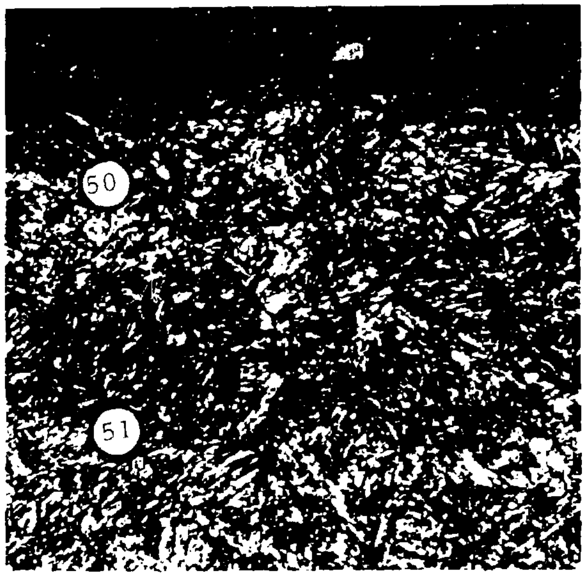
Whenever untempered/overtempered martensite is present, however, as in the case of all of the abusively ground samples, it would appear that this damage has an overriding effect and is the controlling factor in determining the fatigue strength exhibited by the material, see Figure 139.



(a) Surface Finish
Perpendicular to lay: 8 AA
Parallel to lay: 6 AA



(b) Surface Finish
Perpendicular to lay: 65 AA
Parallel to lay: 31 AA



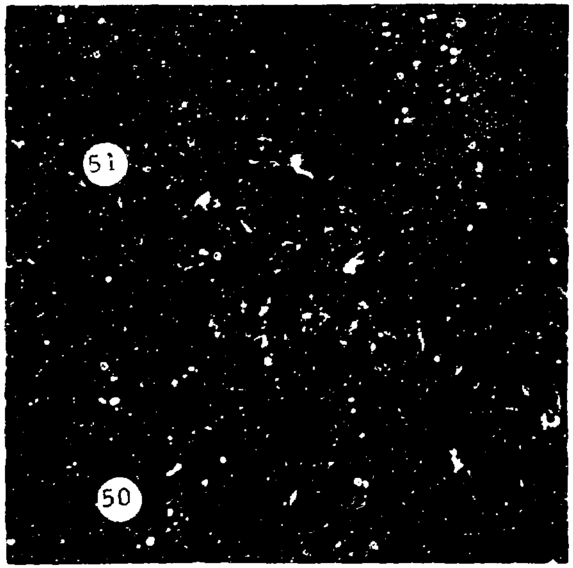
(c) Surface Finish
Perpendicular to lay: 127 AA
Parallel to lay: 40 AA

No visible surface alterations other than change in roughness can be detected. Surface finish values are averages of six to eight specimens in each group. Hardness data shown on microstructures are equivalent R_c values converted from Knoop microhardness data.

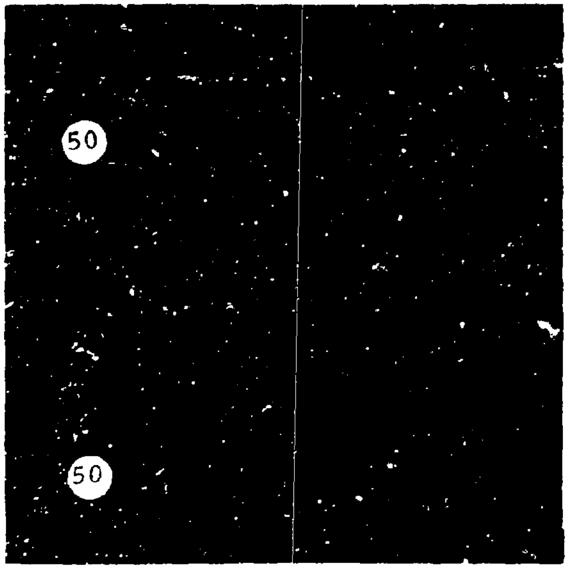
Magnifications: 1000X

ORIENTATION: LONGITUDINAL GRIND. SURFACE SECTIONS PERPENDICULAR TO GRINDING LAY.

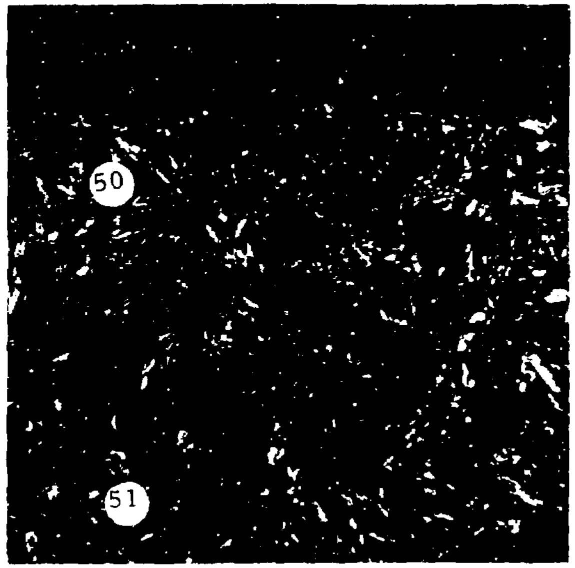
Figure 131
SURFACE CHARACTERISTICS OF AISI 4340 STEEL (QUENCHED AND TEMPERED, 50 R_c) OVER A WIDE RANGE OF SURFACE ROUGHNESS PRODUCED BY GENTLE SURFACE GRINDING



(a) Surface Finish
Perpendicular to lay: 8 AA
Parallel to lay: 6 AA



(b) Surface Finish
Perpendicular to lay: 65 AA
Parallel to lay: 31 AA



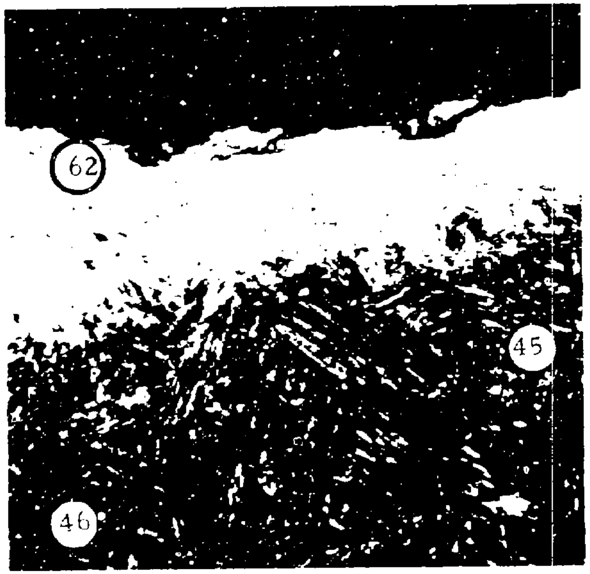
(c) Surface Finish
Perpendicular to lay: 127 AA
Parallel to lay: 40 AA

No visible surface alterations are present. The tendency to form surface laps or folds is evident, and it is seen to be more predominant in the rougher surfaces. Surface finishes are averages of six to eight specimens in each group. Hardness data shown on microstructures are equivalent R_c values converted from Knoop microhardness data.

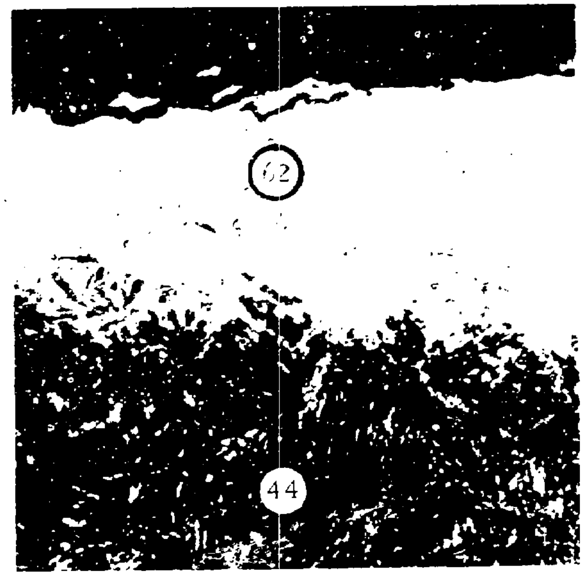
Magnifications: 1000X

ORIENTATION: LONGITUDINAL GRIND. SURFACE SECTIONS PARALLEL TO GRINDING LAY.

Figure 132
SURFACE CHARACTERISTICS OF AISI 4340 STEEL (QUENCHED AND TEMPERED, 50 R_c) OVER A WIDE RANGE OF SURFACE ROUGHNESS PRODUCED BY GENTLE SURFACE GRINDING



(a) Surface Finish
Perpendicular to lay: 29 AA
Parallel to lay: 16 AA



(b) Surface Finish
Perpendicular to lay: 64 AA
Parallel to lay: 34 AA

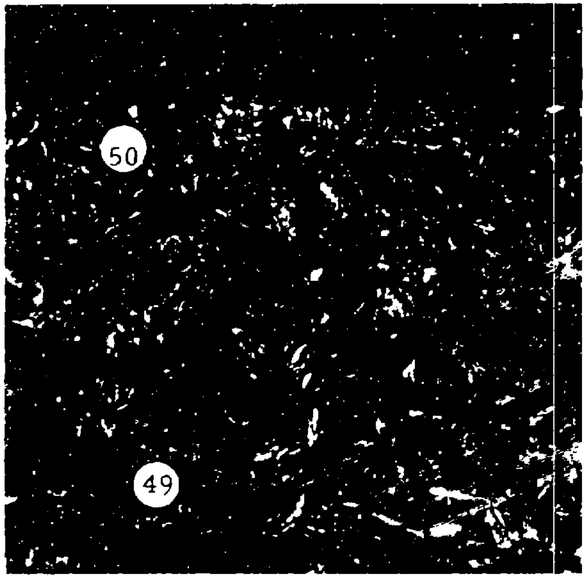
(c) Surface Finish
Perpendicular to lay: 97 AA
Parallel to lay: 46 AA

Characteristic layers of untempered martensite (light etching) are visible on the surfaces of all samples. These surfaces also exhibit the softened overtempered zone immediately beneath the untempered martensite layer. The total heat affected zone, consisting of rehardening and underlying softening, extends to a depth of .002 to .005 in. in most cases. Hardness values indicated on the photomicrographs are R_c data converted from Knoop microhardness measurements. Surface finish measurements are averages of the six to eight specimens in each group.

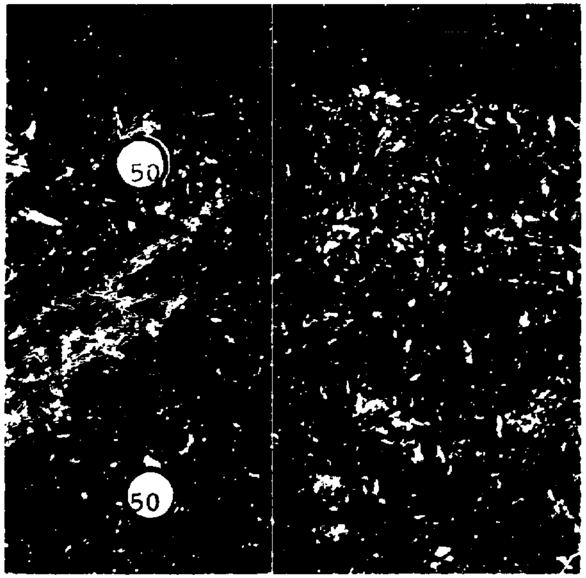
Magnifications: 1000X

ORIENTATION: LONGITUDINAL GRIND. SURFACE SECTIONS PERPENDICULAR TO GRINDING LAY.

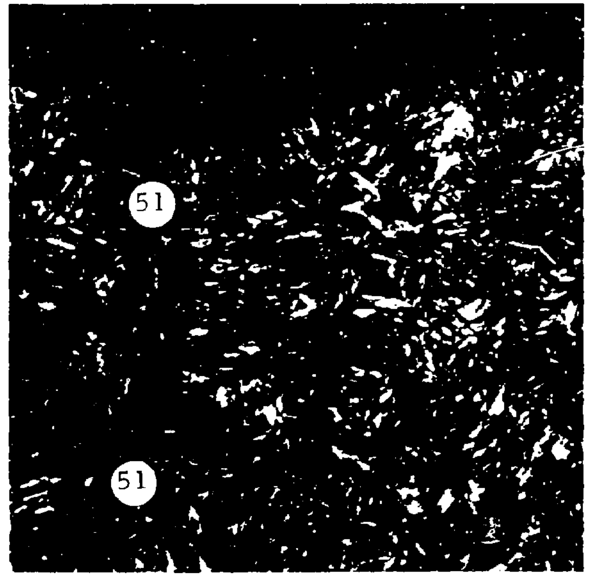
Figure 133
SURFACE CHARACTERISTICS OF AISI 4340 STEEL (QUENCHED AND TEMPERED, 50 R_c)
OVER A WIDE RANGE OF SURFACE ROUGHNESS
PRODUCED BY ABUSIVE SURFACE GRINDING



(a) Surface Finish
Perpendicular to lay: 11 AA
Parallel to lay: 7 AA



(b) Surface Finish
Perpendicular to lay: 58 AA
Parallel to lay: 22 AA



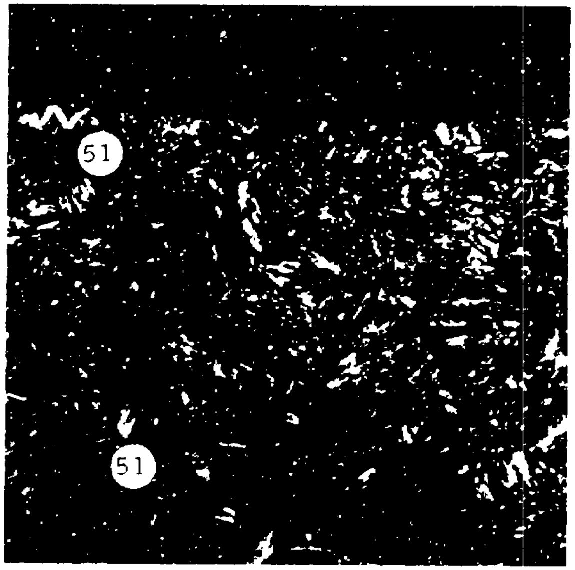
(c) Surface Finish
Perpendicular to lay: 128 AA
Parallel to lay: 35 AA

No visible surface alterations other than change in roughness can be detected. Surface finish values are averages of six to eight specimens in each group. Hardness data shown on microstructures are equivalent R_c values converted from Knoop microhardness data.

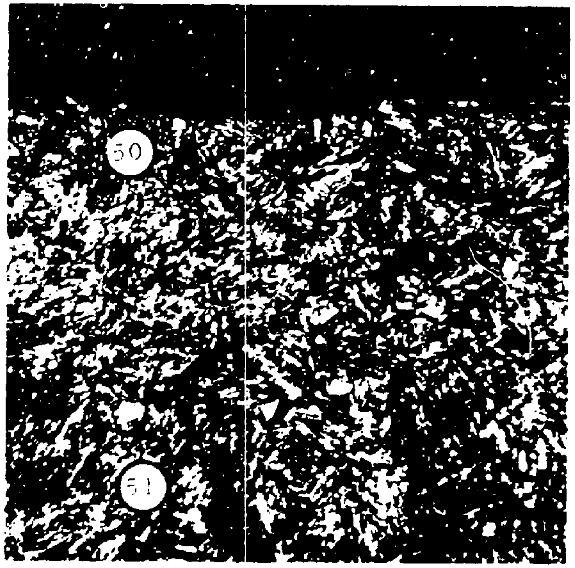
Magnifications: 1000X

ORIENTATION: TRANSVERSE GRIND. SURFACE SECTIONS PERPENDICULAR TO GRINDING LAY.

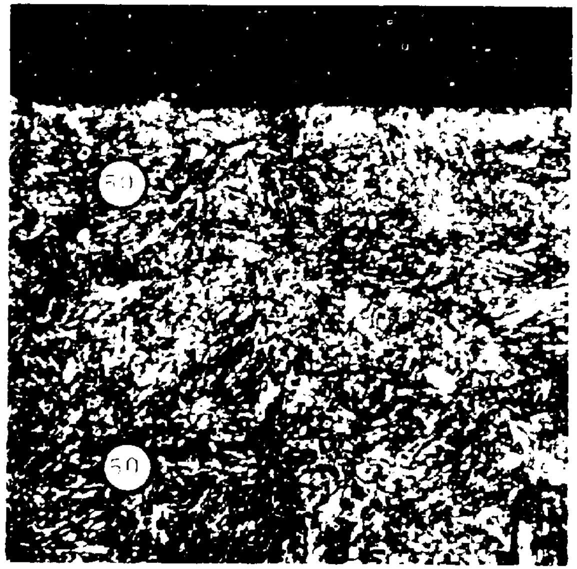
Figure 134
SURFACE CHARACTERISTICS OF AISI 4340 STEEL (QUENCHED AND TEMPERED, 50 R_c) OVER A WIDE RANGE OF SURFACE ROUGHNESS PRODUCED BY GENTLE SURFACE GRINDING



(a) Surface Finish
Perpendicular to lay: 11 AA
Parallel to lay: 7 AA



(b) Surface Finish
Perpendicular to lay: 58 AA
Parallel to lay: 22 AA



(c) Surface Finish
Perpendicular to lay: 128 AA
Parallel to lay: 35 AA

No visible surface alterations are evident. An increase in the tendency to form surface laps or folds can be seen in the rougher surfaces. Surface finish values are averages of six to eight specimens in each group. Hardness data shown on microstructures are equivalent R_c values converted from Knoop microhardness data.

Magnification: 1000X

ORIENTATION: TRANSVERSE GRIND. SURFACE SECTIONS PARALLEL TO GRINDING LAY.

Figure 135
SURFACE CHARACTERISTICS OF AISI 4340 STEEL (QUENCHED AND TEMPERED, 50 R_c)
OVER A WIDE RANGE OF SURFACE ROUGHNESS
PRODUCED BY GENTLE SURFACE GRINDING

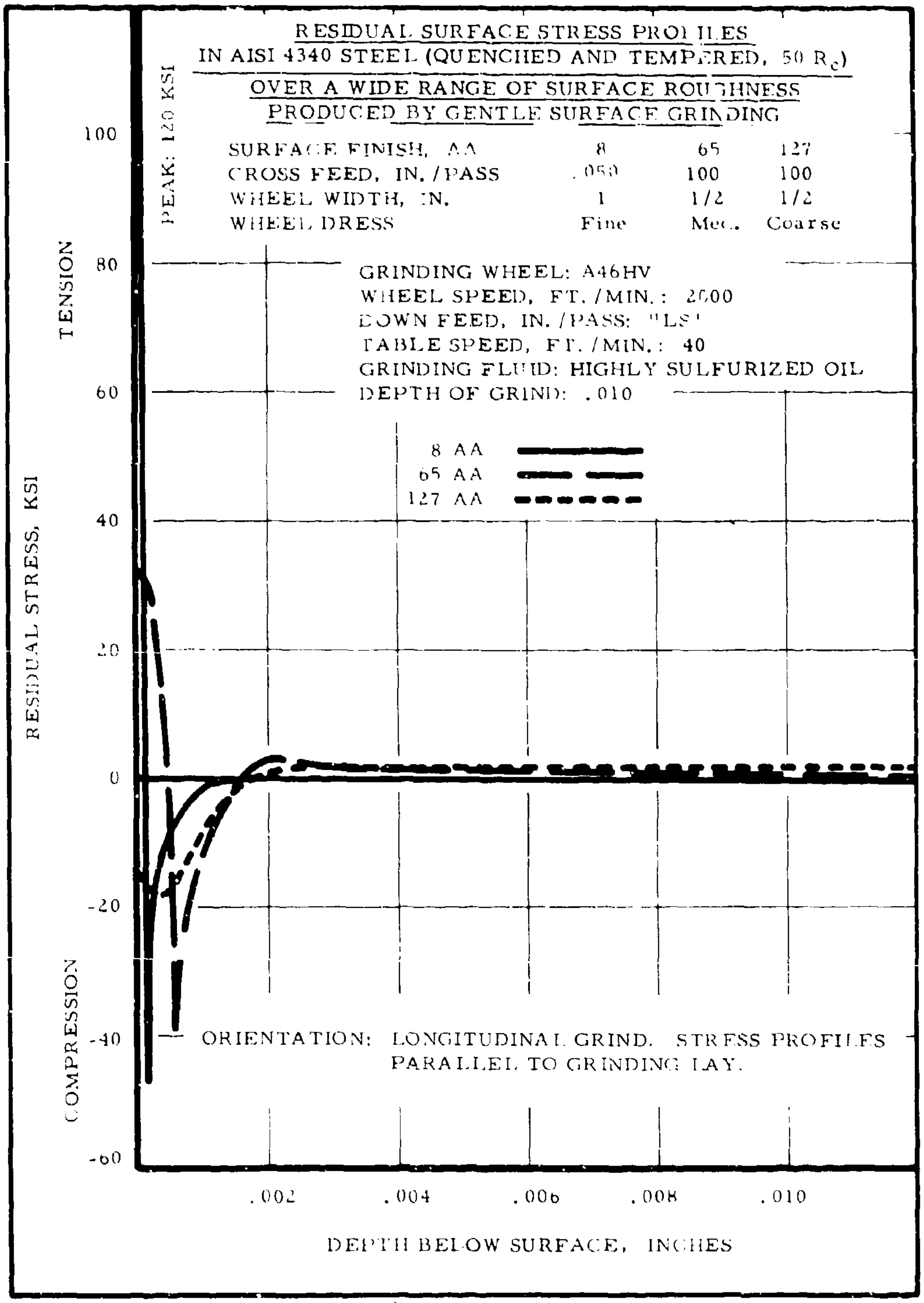


Figure 136
RESIDUAL STRESS IN AISI 4340:
GENTLE SURFACE GRINDING

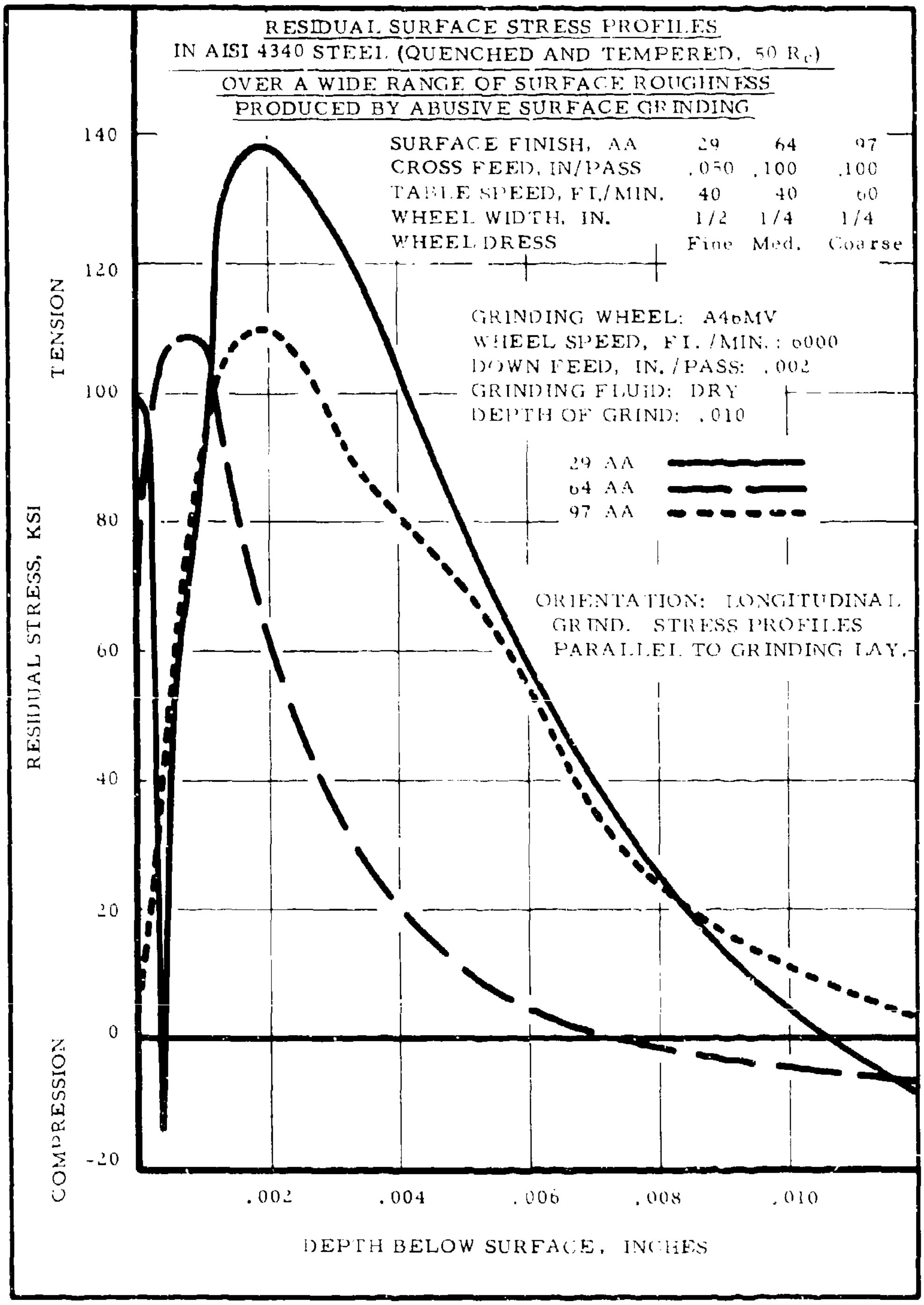


Figure 137
RESIDUAL STRESS IN AISI 4340:
ABUSIVE SURFACE GRINDING

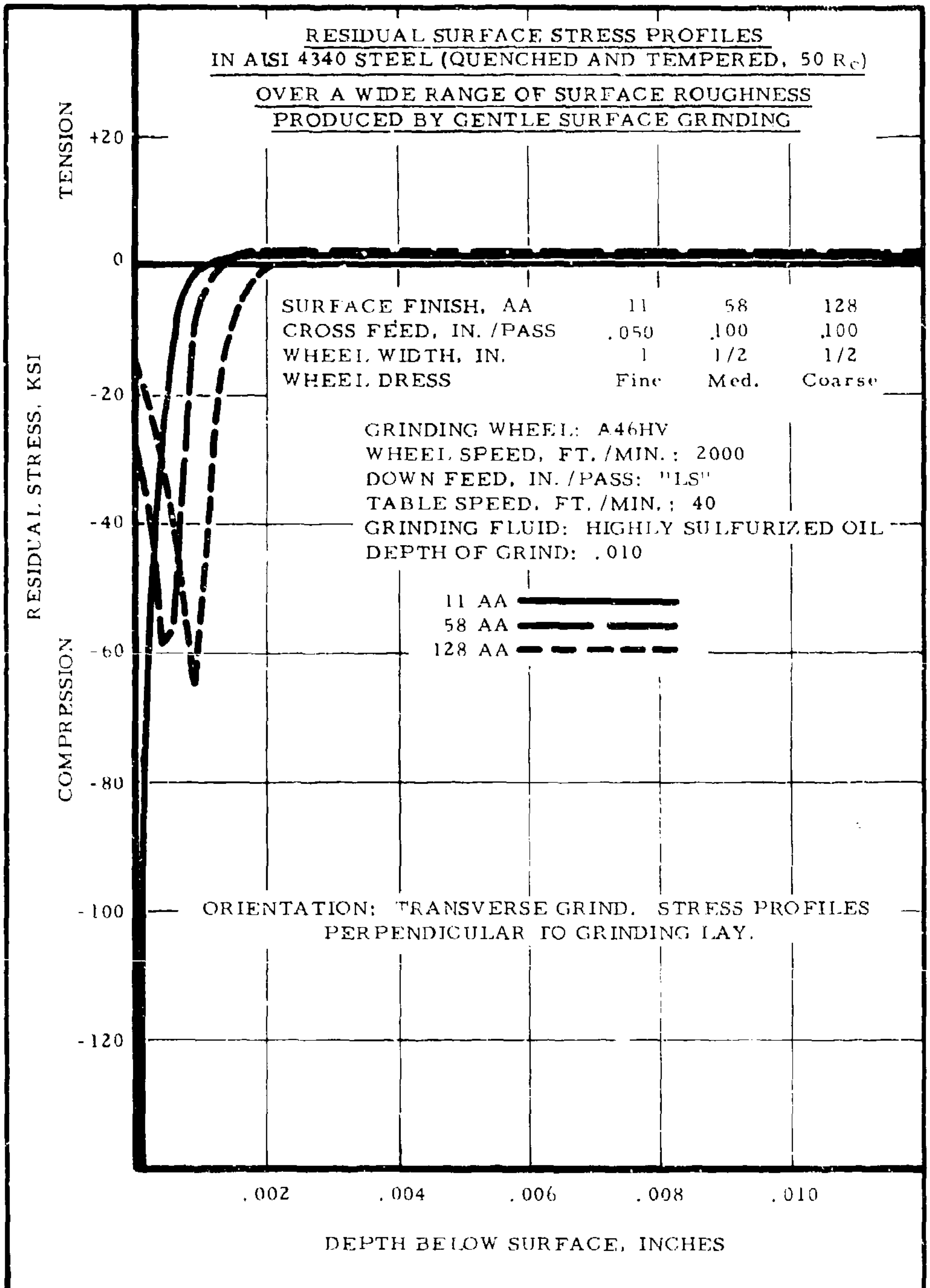


Figure 138
RESIDUAL STRESS IN AISI 4340:
GENTLE SURFACE GRINDING

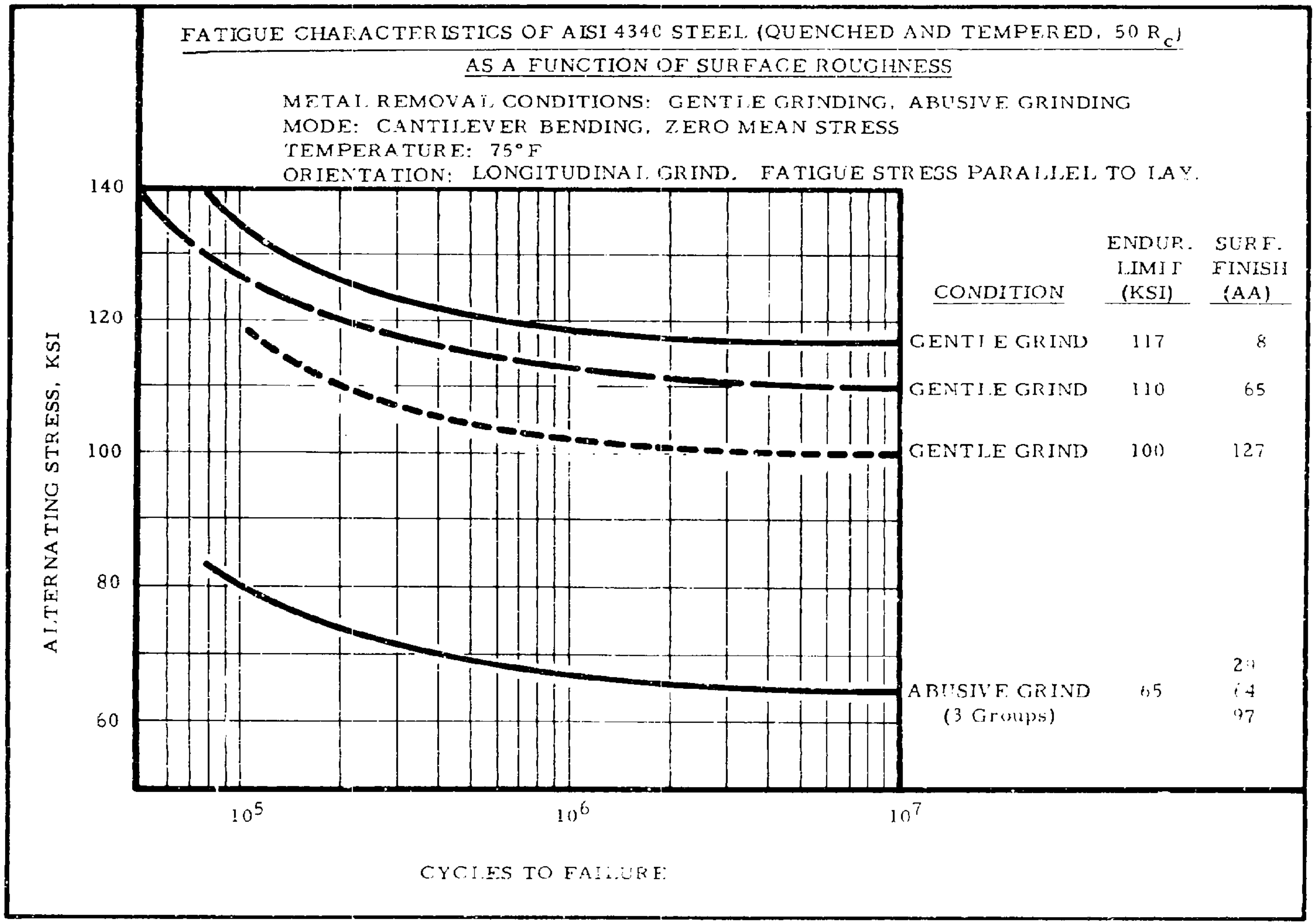


Figure 139
HIGH CYCLE FATIGUE OF AISI 4340:
SURFACE ROUGHNESS

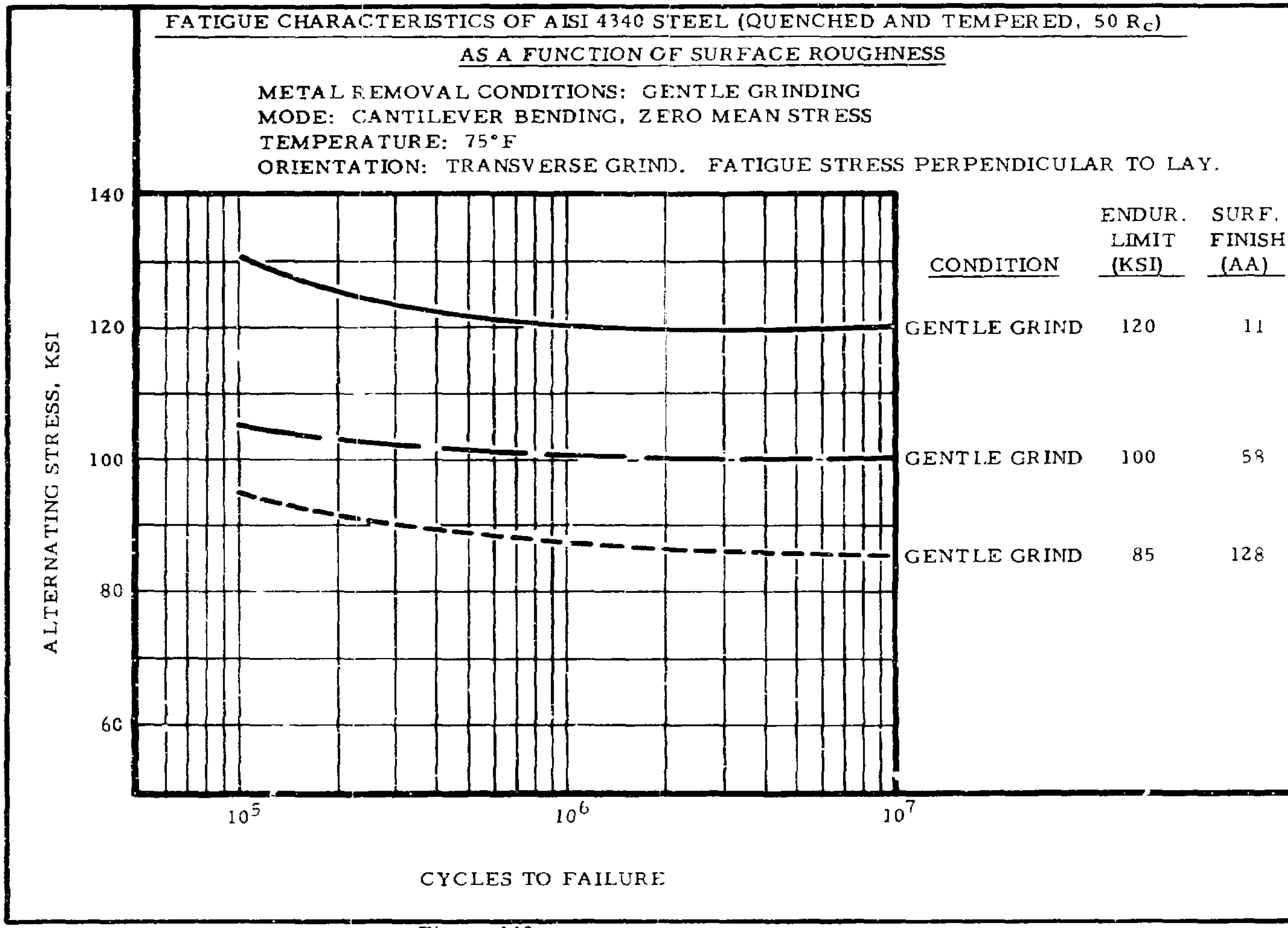


Figure 140
HIGH CYCLE FATIGUE OF AISI 4340:
SURFACE ROUGHNESS

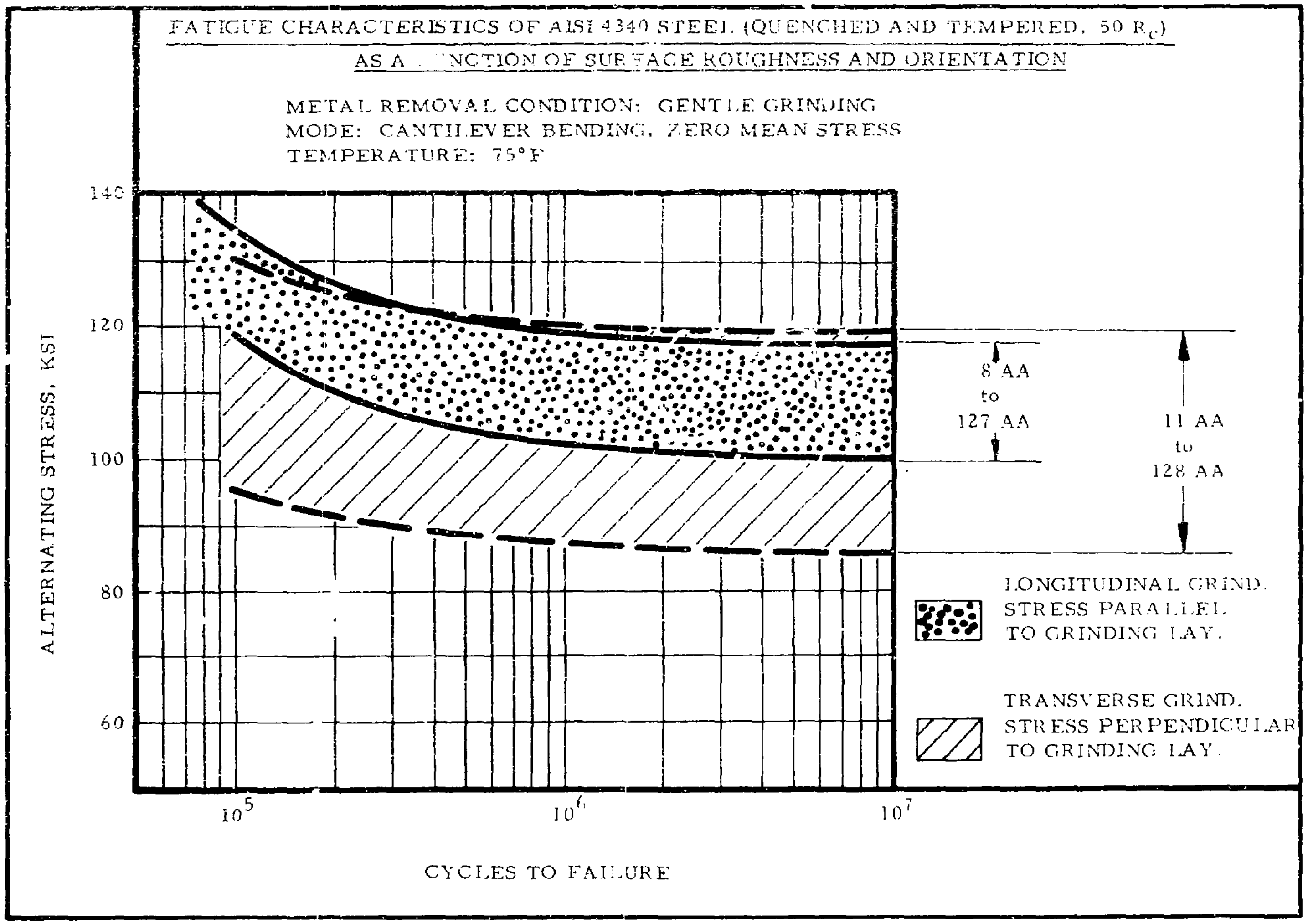


Figure 141
HIGH CYCLE FATIGUE OF AISI 4340:
SURFACE ROUGHNESS AND ORIENTATION

6.11.2 Surface Finish Study: End Milling, Ti-6Al-6V-2Sn, STA, 42 R_c

Metallography

Surface alterations produced in this alloy by gentle end milling-end cutting conditions are shown in Figure 142. Using transverse milling, surface finishes varying from 13 to 125 AA were developed by varying tool geometry. In general, an increase in the apparent surface roughness, as judged at 1000X, can be seen in these photomicrographs, all of which are perpendicular to the lay of the surface. Slight surface alterations are visible indicative of plastic deformation at the surface. The visible depth of this penetration does not exceed .0002 in., although the actual depth of deformation may be somewhat greater. Microhardness measurements, which are indicated on the photomicrographs, show a significant degree of surface softening in these samples. While the alloy had a base hardness in the range of 41 to 42 R_c, surface softening of five to ten points R_c was observed in the first .001 in. beneath the cut surface. This is probably associated either with plastic deformation in this zone or with localized heating produced during the cutting operation. Surface finish measurements were made both perpendicular and parallel to the lay of the surface. The average hardness characteristics of the several samples in each test group are also indicated in Figure 142.

Residual Stress

Residual stress profiles measured in end milled Ti-6Al-6V-2Sn are shown in Figure 143. These data indicate a very similar residual stress condition produced by the three gentle milling conditions being evaluated. As had been found in the facing operation on Inconel 718, the gentle cutting produces the residual compression in the surface.

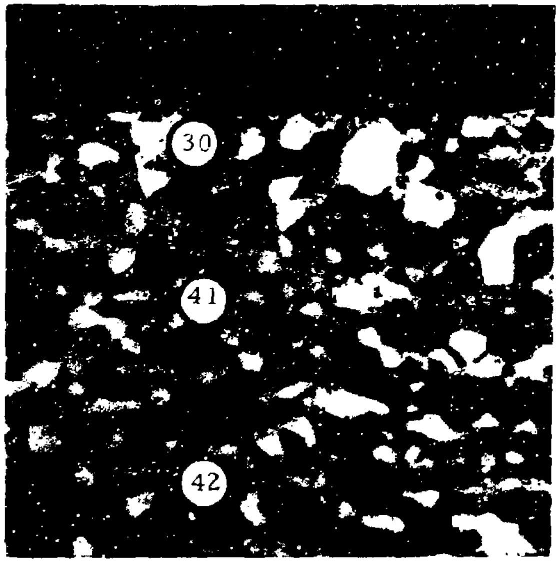
Fatigue Strength

The fatigue behavior of specimens finished by transverse end milling is summarized in Figure 144. The principal fatigue stress was perpendicular to the cutting direction, hence, perpendicular to the lay of the surface. The eight tests run on each of the three surface finish levels all fell on the same curve as shown in Figure 144.

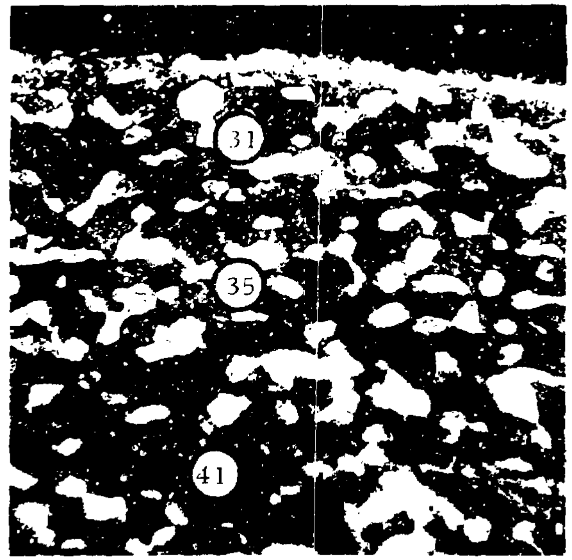
6.11.2 Surface Finish Study: End Milling, Ti-6Al-6V-2Sn, STA, 42 R_c (continued)

Fatigue Strength (continued)

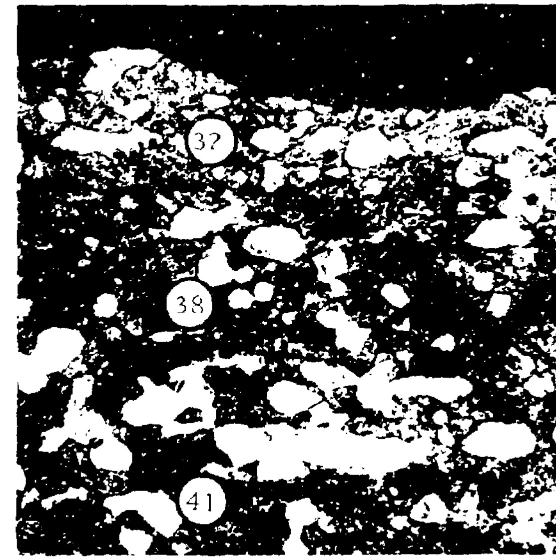
An endurance limit of 82 ksi was indicated by these tests. The fatigue data are summarized in Table XXVII. As in the case of turning or facing Inconel 718, it is shown that the fatigue strength of titanium is unaffected by changes in surface finish produced by gentle milling conditions over the range studied. The equivalence of the residual stress profile and of the microstructural condition of the three groups of samples contained in this titanium study substantiates the conditions hoped for in running this test series; namely, that the isolated effect of surface finish per se could be evaluated.



(a) Surface Finish
Perpendicular to lay: 13 AA
Parallel to lay: 8 AA



(b) Surface Finish
Perpendicular to lay: 55 AA
Parallel to lay: 13 AA



(c) Surface Finish
Perpendicular to lay: 125 AA
Parallel to lay: 18 AA

Slight surface alterations may be seen, particularly in the case of Figure (b) above. These are indicative of plastic deformation at the surface. Microhardness data show softening in these surfaces, probably associated with either plastic deformation or with localized heating produced during cutting. The microhardness data indicated are R_c values converted from Knoop microhardness measurements. Surface finish readings are averages of six to eight specimens in each group.

Magnifications: 1000X

ORIENTATION: TRANSVERSE MILL. SURFACE SECTIONS PERPENDICULAR TO LAY.

Figure 142
SURFACE CHARACTERISTICS OF TI-6Al-6V-2Sn (SOL. TREATED AND AGED, 42 R_c) OVER A WIDE RANGE OF SURFACE ROUGHNESS PRODUCED BY GENTLE END MILLING - END CUTTING

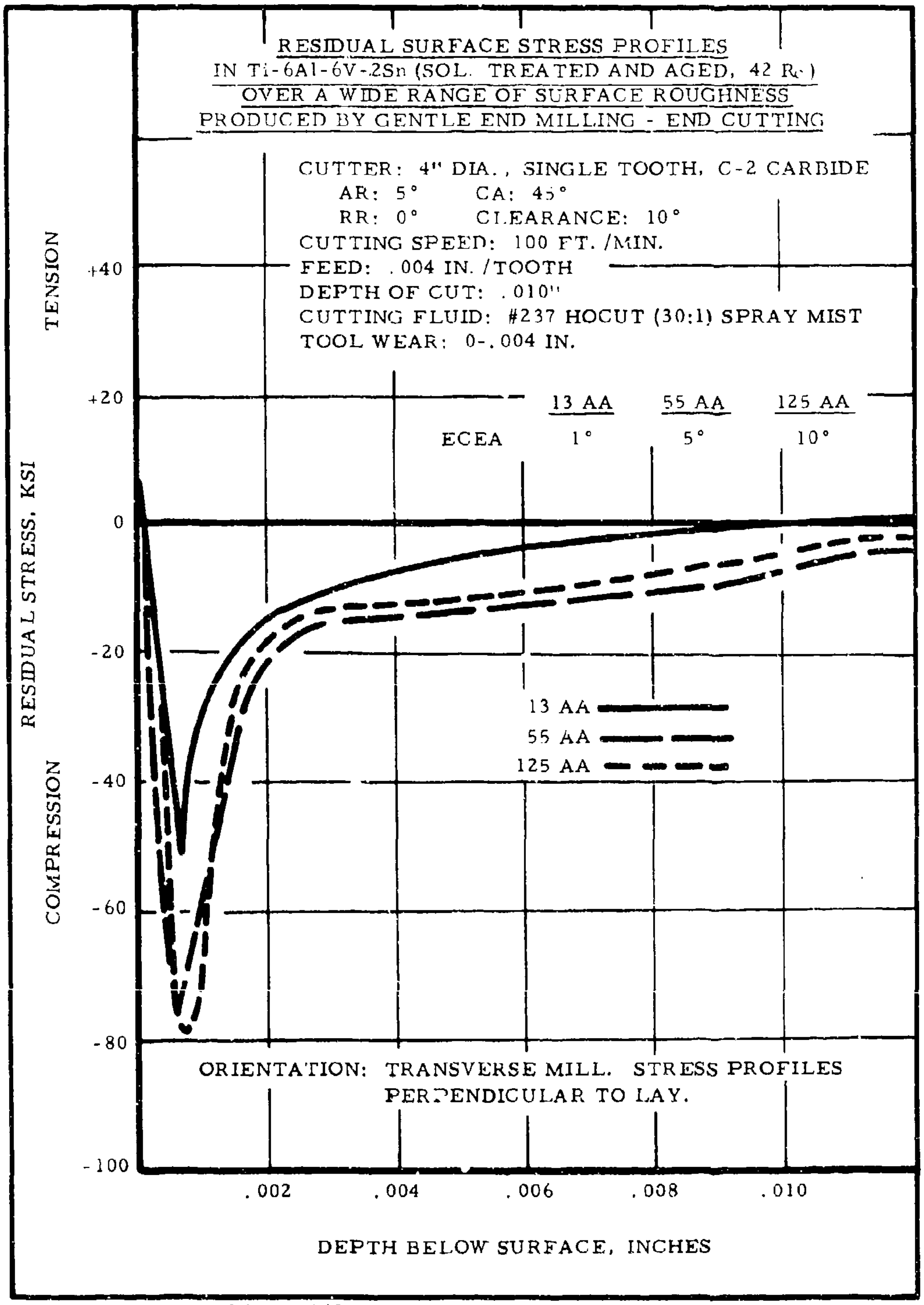


Figure 143
RESIDUAL STRESS IN TITANIUM 6Al-6V-2Sn:
GENTLE END MILLING - END CUTTING

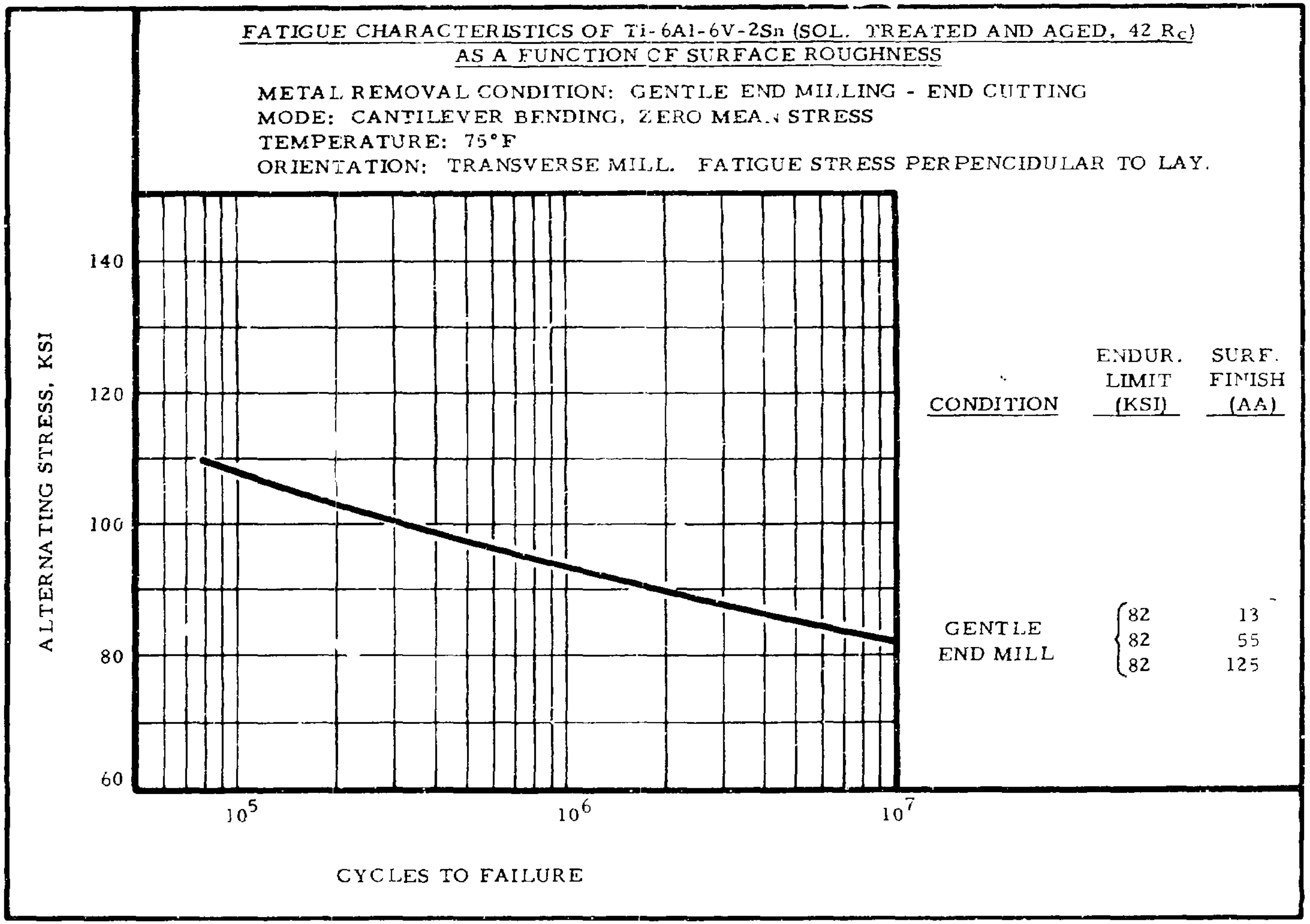


Figure 144
HIGH CYCLE FATIGUE OF TITANIUM 6Al-6V-2Sn:
SURFACE ROUGHNESS

6.11.3 Surface Finish Study: Turning, Inconel 718, STA, 44 R_c

Metallography

Photomicrographs summarizing the surface metallurgy observed in transverse turning of Inconel 718 are shown in Figures 145 and 146. Figure 145 shows three different surface finishes ranging from 25 to 118 AA produced by a gentle turning operation. Figure 146 shows a single sample of Inconel 718 produced by an abusive turning operation. The particular conditions chosen resulted in a surface finish of 76 AA on the abusively cut samples. All of these photomicrographs show a surface section which is parallel to the direction of tool travel. Microhardness measurements were made on several samples from each of the surface finish groups.

Slight surface softening was measured under gentle machining conditions. Softening and an underlying zone of slightly increased hardness was observed in the case of abusively turned samples. A combination of localized surface heating and plastic deformation are believed responsible for these reactions.

Surface finish measurements were made both perpendicular and parallel to the lay of the surface. These are also summarized in Figures 145 and 146.

Residual Stress

The residual stress profiles measured for the three gently turned and one abusively turned samples of Inconel 718 are shown in Figure 147. These data are for the residual stress in the surface perpendicular to the cutting direction since all samples were turned in the transverse direction. Note that all of the gently turned surfaces exhibit very similar residual stress patterns, showing a peak compressive stress of approximately 50 ksi. The abusive sample shows a much deeper residual compressive stress, obtaining a peak level of approximately 120 ksi. Notice also that the abusively cut sample shows a total depth of stressed surface considerably in excess of .010 inches. All of the gently turned surfaces, however, indicate a much shallower depth

Residual Stress (continued)

of surface alteration. This residual stress behavior is similar to that which has been seen previously in milling operations. The general tendency, again confirmed here, is that gentle cutting produces compressive surface stresses of relatively low order, while abusive cutting (associated with dull tools) produces residual compressive stresses, but of considerably greater magnitude. This is in contrast to grinding operations, in which case residual stresses associated with abusive operations are generally tensile in nature.

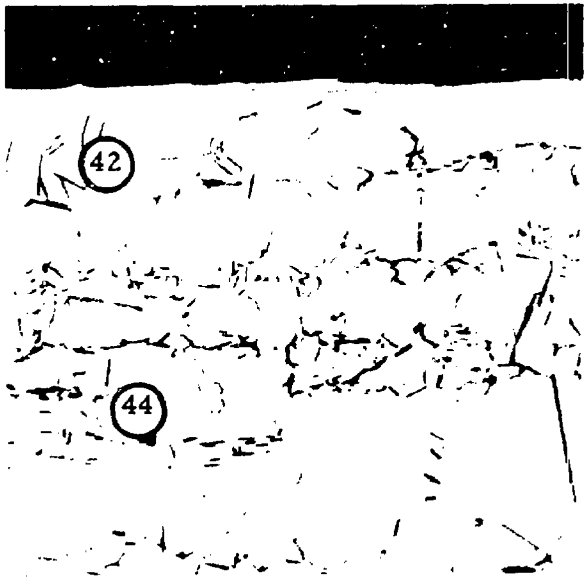
Fatigue Strength

The fatigue behavior of the four groups of Inconel 718 surface finish samples was determined by running standard S/N curves. Specimens were turned or faced in the transverse direction. For this reason, the principal fatigue stress was perpendicular to the lay of the surface. Seven to eight tests were run at each surface finish level. These exhibited fatigue lives ranging from 10^5 to 10^7 cycles. These data are summarized in Table XXVII.

In plotting the data, however, all of the points from the four groups of samples fell on the single fatigue curve shown in Figure 148. These data indicate an endurance limit for this material of 60 ksi in all of the conditions studied. It is interesting to note that in the previous surface integrity contract,* gentle surface grinding applied to Inconel 718 also exhibited an endurance limit of 60 ksi when tested under the same conditions. It would appear that this alloy is insensitive to differences in surface finish in turning over the range of finishes covered by this study.

It should be pointed out, however, that abusive turning procedures are still an area of concern in component manufacture since the higher residual stresses associated with them (see Figure 147) can lead to distortion problems, even though fatigue strength may not be particularly affected. These comments, however, should be confined to a specific situation such as turning from which the data have been established. In grinding, the abusive condition has been shown to result in fatigue strengths of less than 24 ksi on this alloy.*

* Contract F33615-68-C-1003 (Report No. AFML-TR-70-11).



Surface Finish
Perpendicular to lay: 25 AA
Parallel to lay: 14 AA

Surface Finish
Perpendicular to lay: 58 AA
Parallel to lay: 49 AA

Surface Finish
Perpendicular to lay: 118 AA
Parallel to lay: 26 AA

A slight increase in the degree of plastic deformation at the surface and an increase in the tendency to form tears or laps at the surface is associated with an increase in roughness. No alterations other than plastic deformation were observed. Surface finish values are averages of six to eight specimens in each group. Hardness data shown on the microstructures are equivalent R_c values converted from Knoop microhardness data.

Magnifications: 1000X

ORIENTATION: TRANSVERSE TURN. SURFACE SECTIONS PARALLEL TO LAY.

Figure 145
SURFACE CHARACTERISTICS OF INCONEL 718 (SOL. TREATED AND AGED, 44 R_c)
OVER A WIDE RANGE OF SURFACE ROUGHNESS
PRODUCED BY GENTLE TURNING (FACING)

Surface Finish

Perpendicular to lay: 76 AA
Parallel to lay: 56 AA

A very thin layer of highly deformed metal is visible at the surface. Microhardness data indicate very thin surface softening, possibly due to localized heating and a somewhat hardened underlying layer associated with general plastic deformation in the surface. Hardness data are equivalent R_c values converted from Knoop measurements.

Magnification: 1000X

ORIENTATION: TRANSVERSE TURN. SURFACE SECTIONS PARALLEL TO LAY.

Figure 146
SURFACE CHARACTERISTICS OF INCONEL 718 (SOL. TREATED AND AGED, 44 R_c) OVER A WIDE RANGE OF SURFACE ROUGHNESS PRODUCED BY <u>ABUSIVE TURNING (FACING)</u>

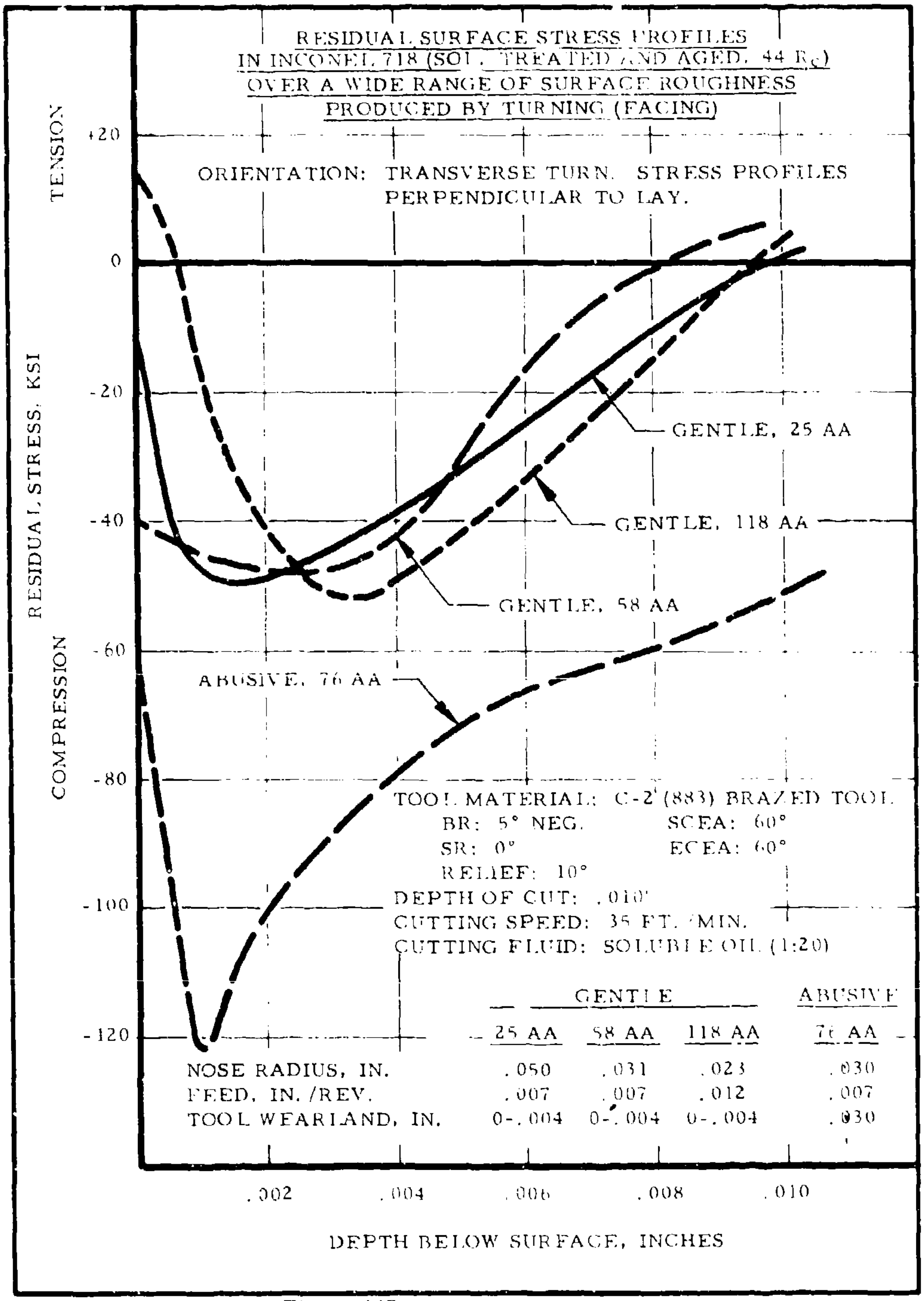


Figure 147
RESIDUAL STRESS IN INCONEL 718:
TURNING (FACING)

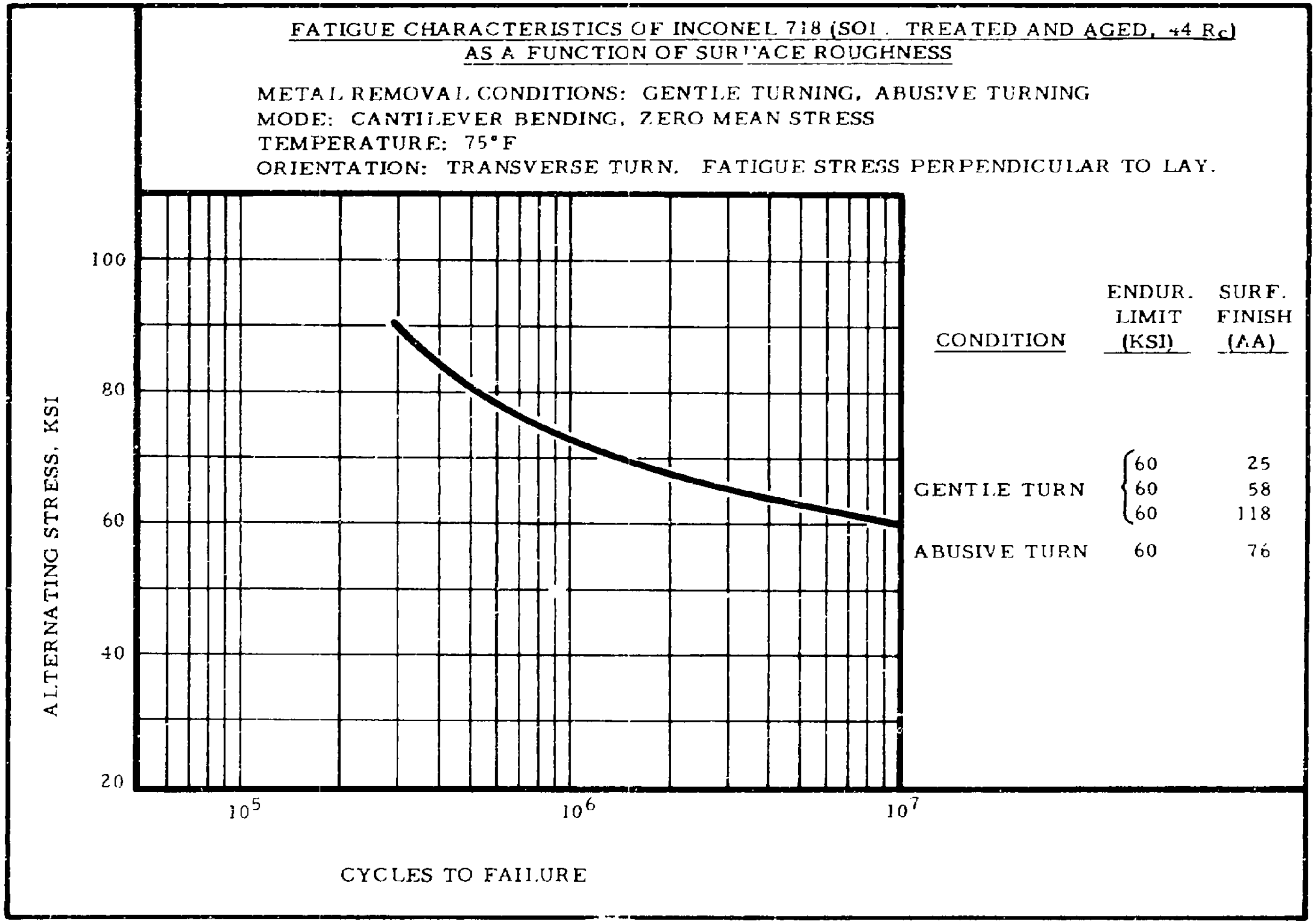


Figure 148
HIGH CYCLE FATIGUE OF INCONEL 718: SURFACE ROUGHNESS

6.12 Additional Comparative Studies

A review of all of the data obtained on the subject contract permits a surface integrity analysis of two different areas of engineering interest. These are the effect of elevated temperature and also the effect of shot peening as a post processing operation.

A summary of high cycle fatigue data obtained on a nickel-base alloy, in this case AF 95, is shown in Figure 149. This series of bar graphs compares the behavior of various alloy/material removal procedures at room temperature versus 1000° F. In general, it may be said that the relative behavior of gentle versus abusive or standard versus off-standard observed at room temperature is carried over to the elevated temperature exposure. In the case of surface grinding at room temperature, for example, endurance limits due to gentle versus abusive grinding were 75 versus 26 ksi. At 1000° F, these values are 98 versus 48 ksi. A discussion concerned with the reasons for the fatigue behavior at 1000° F being higher than at room temperature is contained in Section 6.8.1. The point to be made here is that the comparative relation between gentle and abusive grinding is carried over from room temperature to the elevated temperature exposure. In reviewing Figure 149, the same relative effects may also be seen for ECM and EDM, although in both of these cases little difference in fatigue strength is associated with variations in metal removal parameters.

Also shown in Figure 149 is the effect of shot peening as a post-processing operation and its ability to carry over at elevated temperatures. In the case of the AF 95 which was used for this study, it may be seen that shot peening effects, which enhance fatigue strength at room temperature, do indeed enhance fatigue strength at the 1000° F level. From an overall review of Figure 149, it is probably logical to conclude that surface integrity considerations based on room temperature test data are quite applicable at normal elevated service temperatures of materials. At least this appears to be true in the case of nickel-base alloys. It is also valid to conclude that the merits frequently demonstrated for shot peening in sometimes correcting poor surface integrity and also in enhancing the fatigue strength of parts having a high surface integrity level will also exist in many elevated temperature situations. The effectiveness of shot peening over long periods of time in these situations, however, has not been established.

A summary of the effect of shot peening on a number of room temperature surface integrity situations is shown in Figures 150, 151, and 152. In all cases, shot peening demonstrates an ability to increase fatigue strength, although the proportions of increase are quite variable. The

greatest effect is observed when shot peening is applied to situations which otherwise exhibit relatively poor fatigue strengths. This is particularly evident in Figure 151 which summarizes a number of EDM comparisons. Lesser effects are seen in the case of low stress grinding and of electrolytic polishing as shown in Figure 150.

From a comparison of the data in these three figures, 150-152, the general trend could be concluded that shot peening can elevate the fatigue strength of surfaces machined in a variety of ways to a peak or plateau value characteristic of the alloy being peened. Within limits this is probably valid. It must be remembered, however, that all machined surfaces cannot be shot peened effectively to be consistent with other engineering requirements. Where applicable, however, peening appears to be a potentially useful means for enhancing surface integrity. Specific evaluations must be made, however, in applications where the cyclic strain range or temperature of the component in service may cause decay of the compressive stresses set up by the peening.

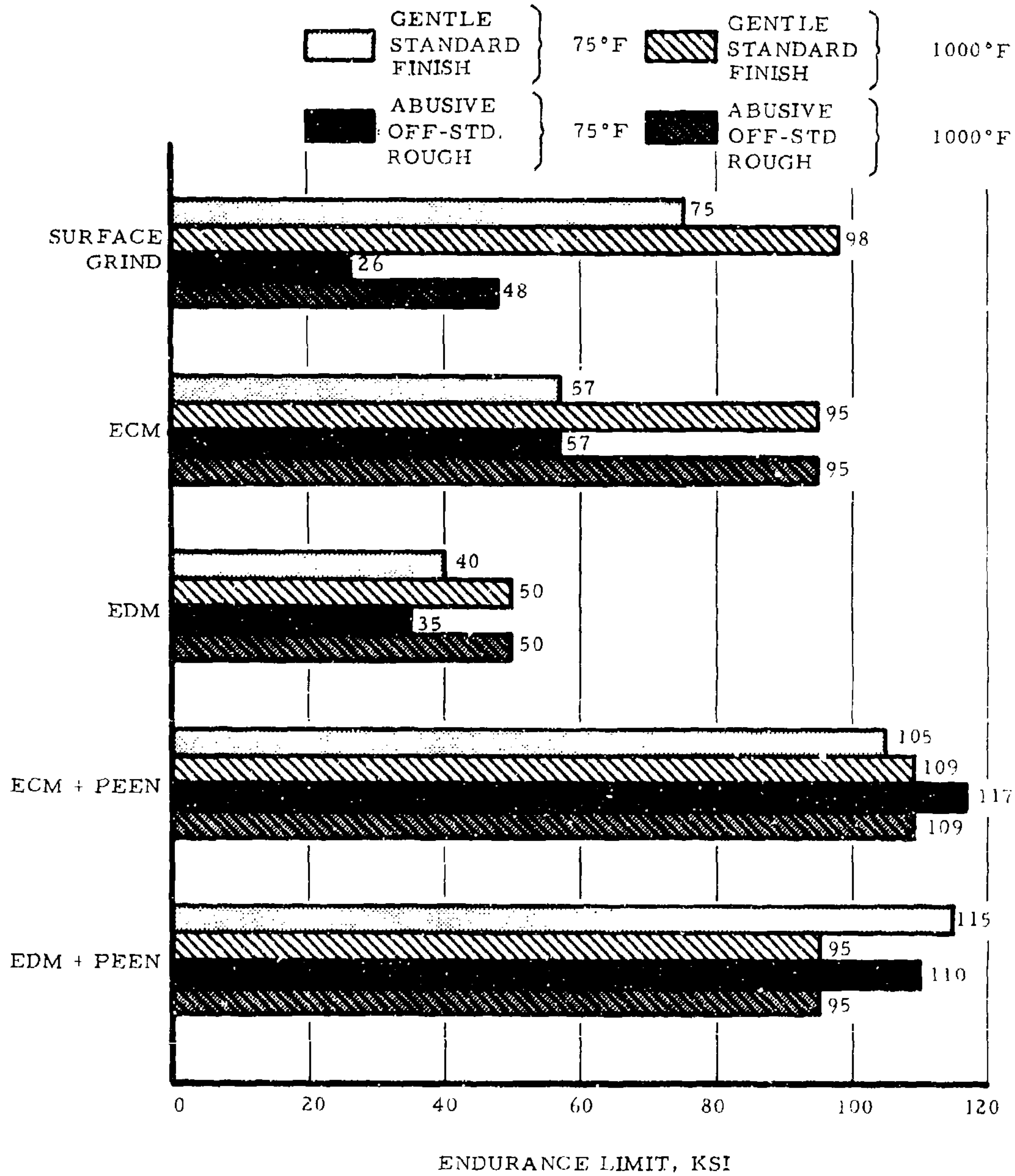


Figure 149
SUMMARY OF HIGH CYCLE FATIGUE BEHAVIOR
OF AF-95 (SOLUTION TREATED AND AGED, 50 R_c)
EFFECT OF TEMPERATURE

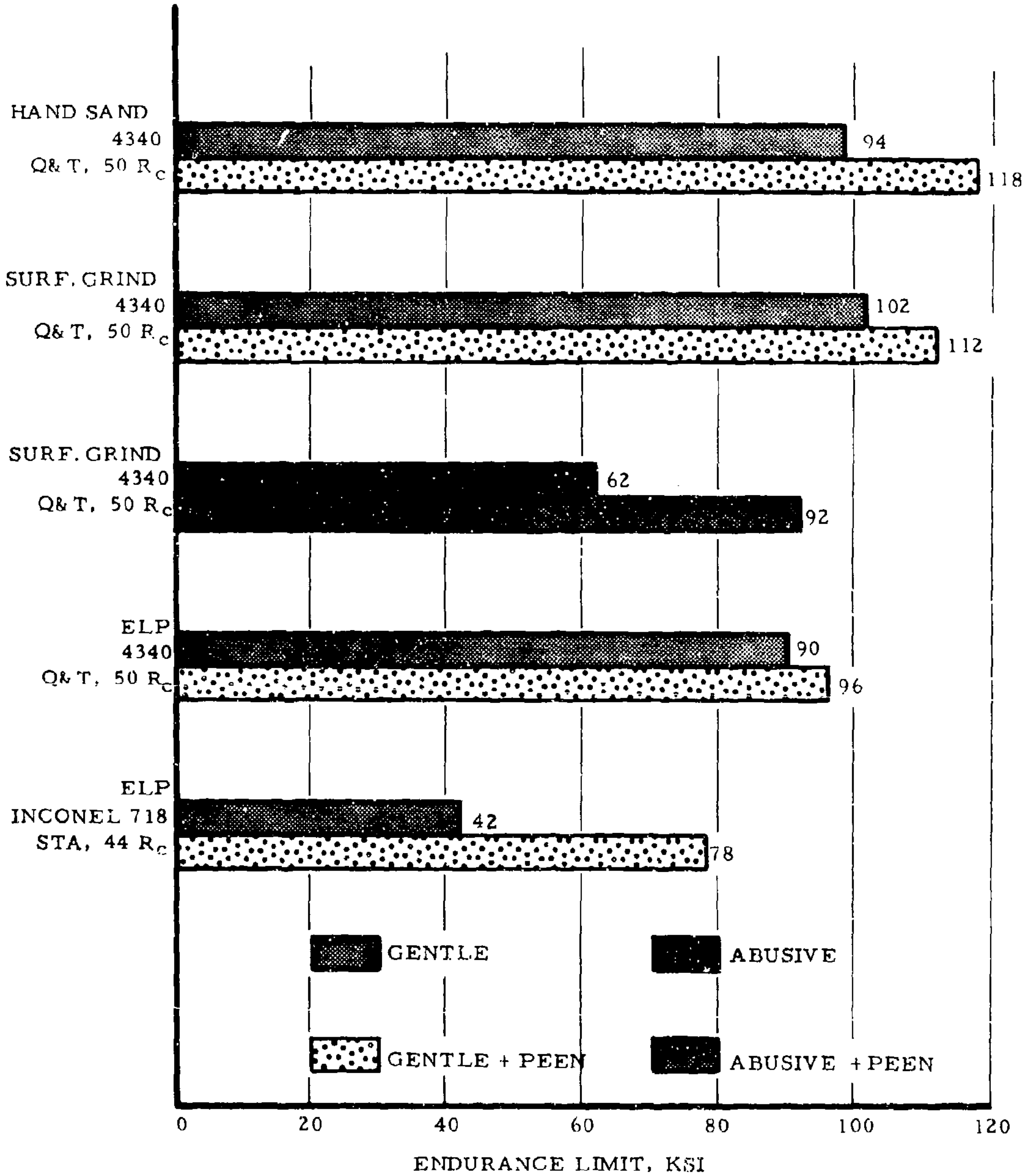


Figure 150
SUMMARY OF HIGH CYCLE FATIGUE RESPONSE
EFFECT OF SHOT PEENING

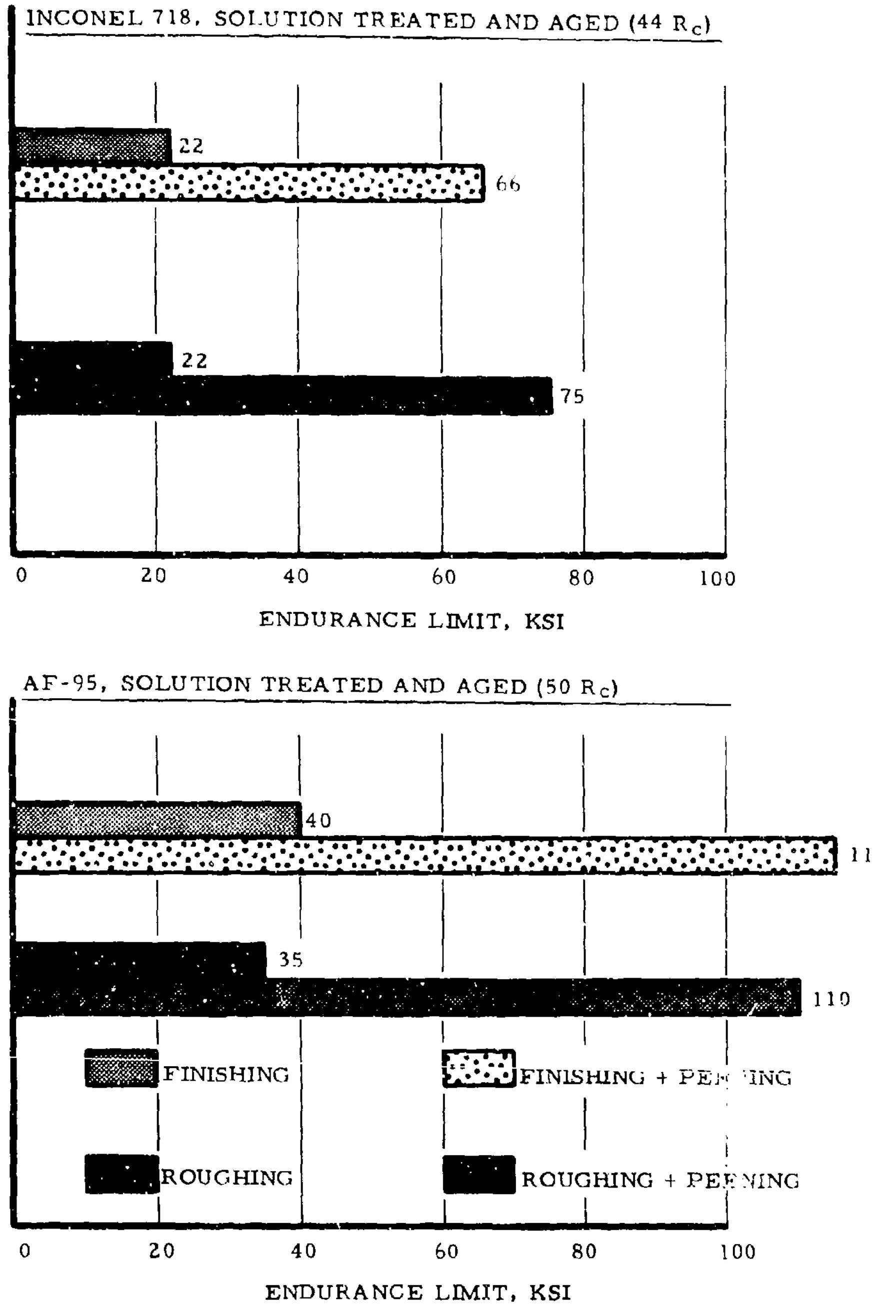


Figure 151
SUMMARY OF HIGH CYCLE FATIGUE RESPONSE: EDM
EFFECT OF SHOT PEENING

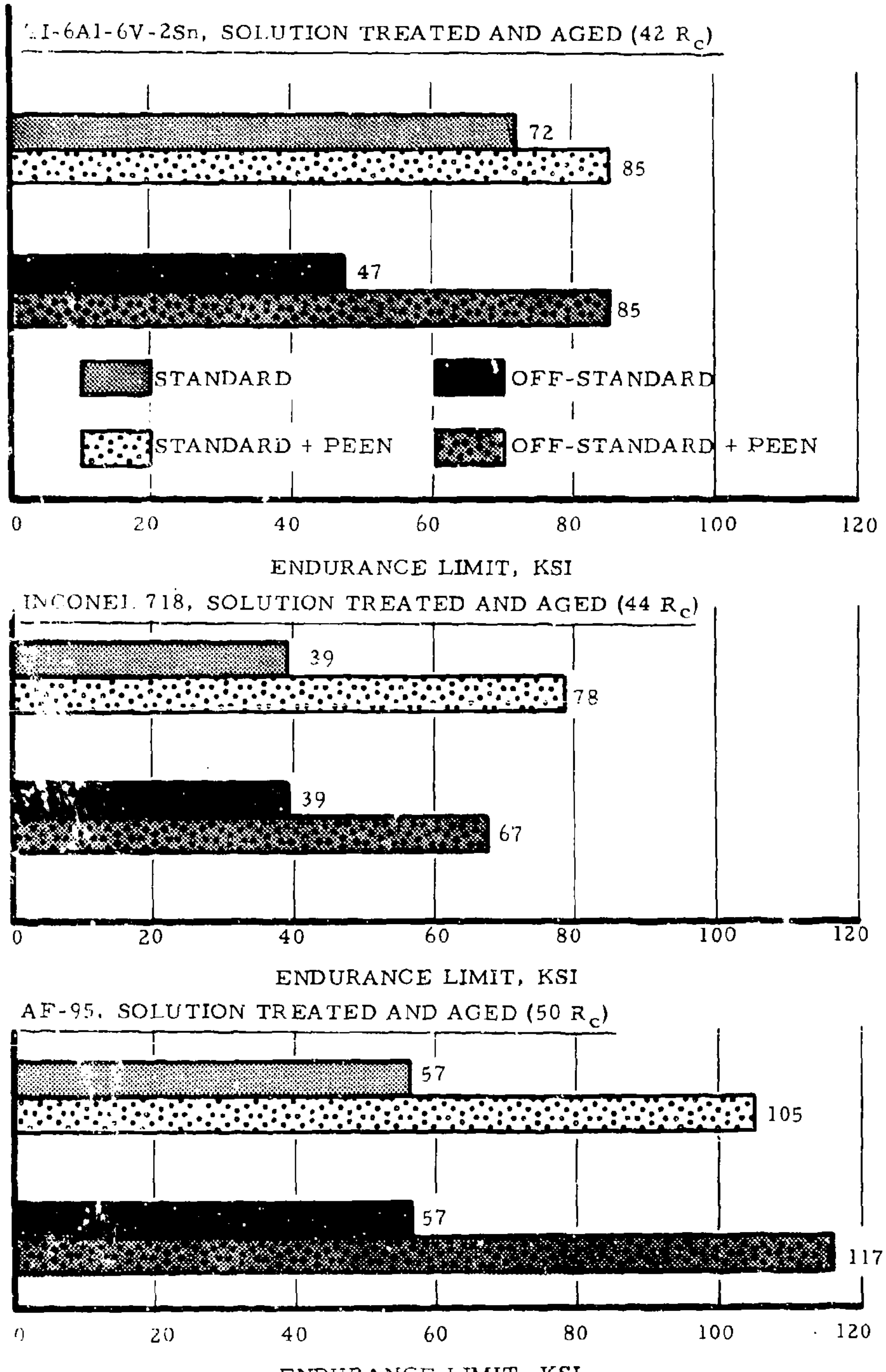


Figure 152
SUMMARY OF HIGH CYCLE FATIGUE RESPONSE: ECM
EFFECT OF SHOT PEENING

6.13 Scanning Electron Microscopy

As part of the overall manufacturing engineering survey, the General Electric Company prepared a number of scanning electron photomicrographs and also some Talysurf traces of various alloy/material removal combinations. At the present time, specific engineering data is not available to permit direct and meaningful interpretation of the information contained in scanning electron photomicrographs to the surface integrity situation. Examples of this work, however, are included in this section for illustrative purposes only. It is anticipated that documentation of this type may prove beneficial in subsequent surface integrity studies. The following illustrations are presented:

Figure 156 - Low Stress Grinding - AF95

Figure 157 - Conventional Grinding - AF95

Figure 158 - Abusive Grinding - AF95

Figure 159 - Talysurf Traces-Surface Ground - AF95

Figure 160 - ECM (Finishing) - Ti-6Al-6V-2Sn

Figure 161 - ECM (Roughing) - Ti-6Al-6V-2Sn

Figure 162 - ECM (Finishing) - AF2-1DA

Figure 163 - ECM (Roughing) - AF2-1DA

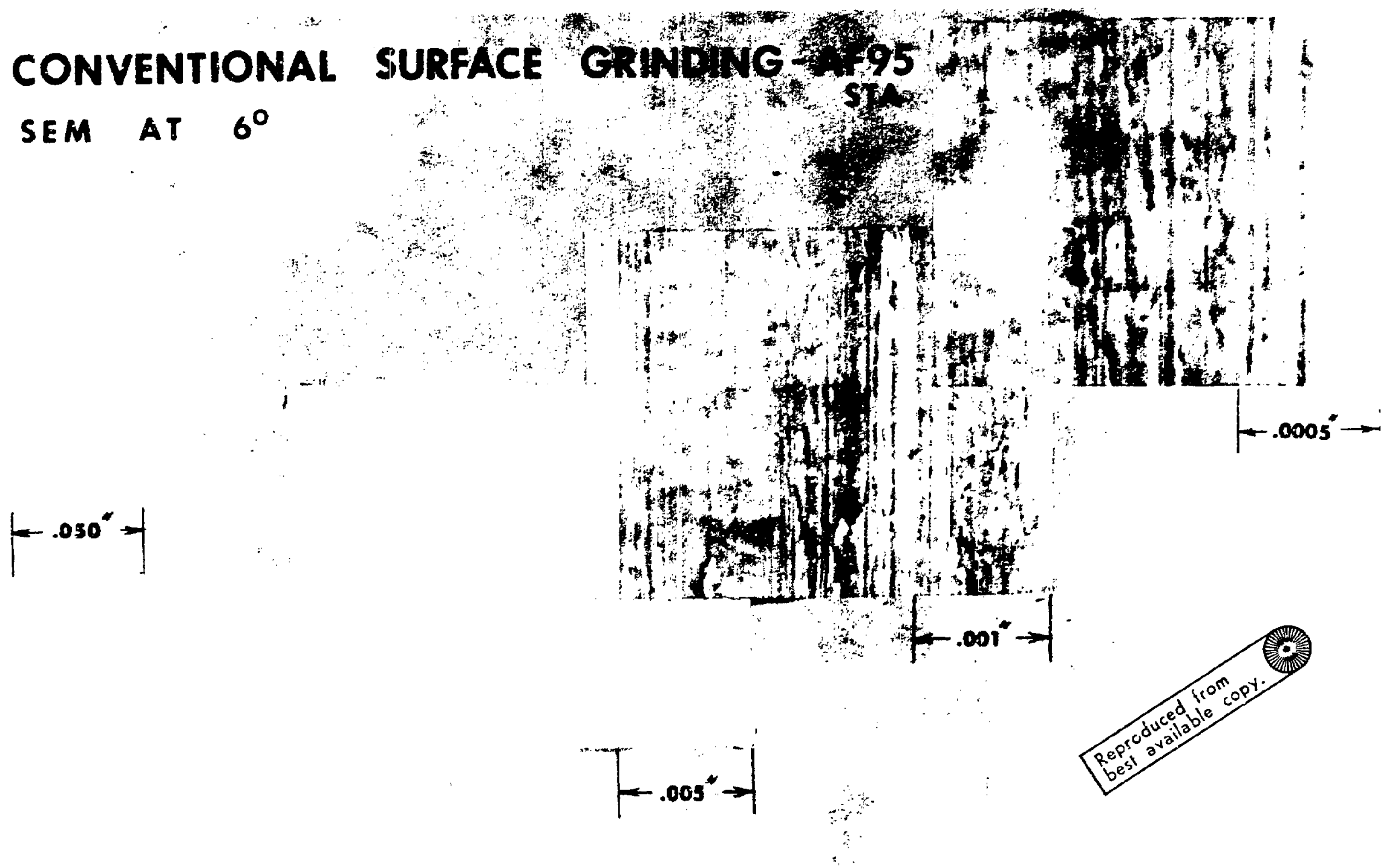
Figure 164 - EDM (Finishing) - AF95

Figure 165 - EDM (Roughing) - AF95

Figure 166 - EDM (Finishing) - Rene' 80

Figure 167 - EDM (Roughing) - Rene' 80

Figure 153
SCANNING ELECTRON PHOTOMICROGRAPHS:
LOW STRESS GRINDING - AF95



GENERAL ELECTRIC

Figure 154
SCANNING ELECTRON PHOTOMICROGRAPHS:
CONVENTIONAL GRINDING - AF95

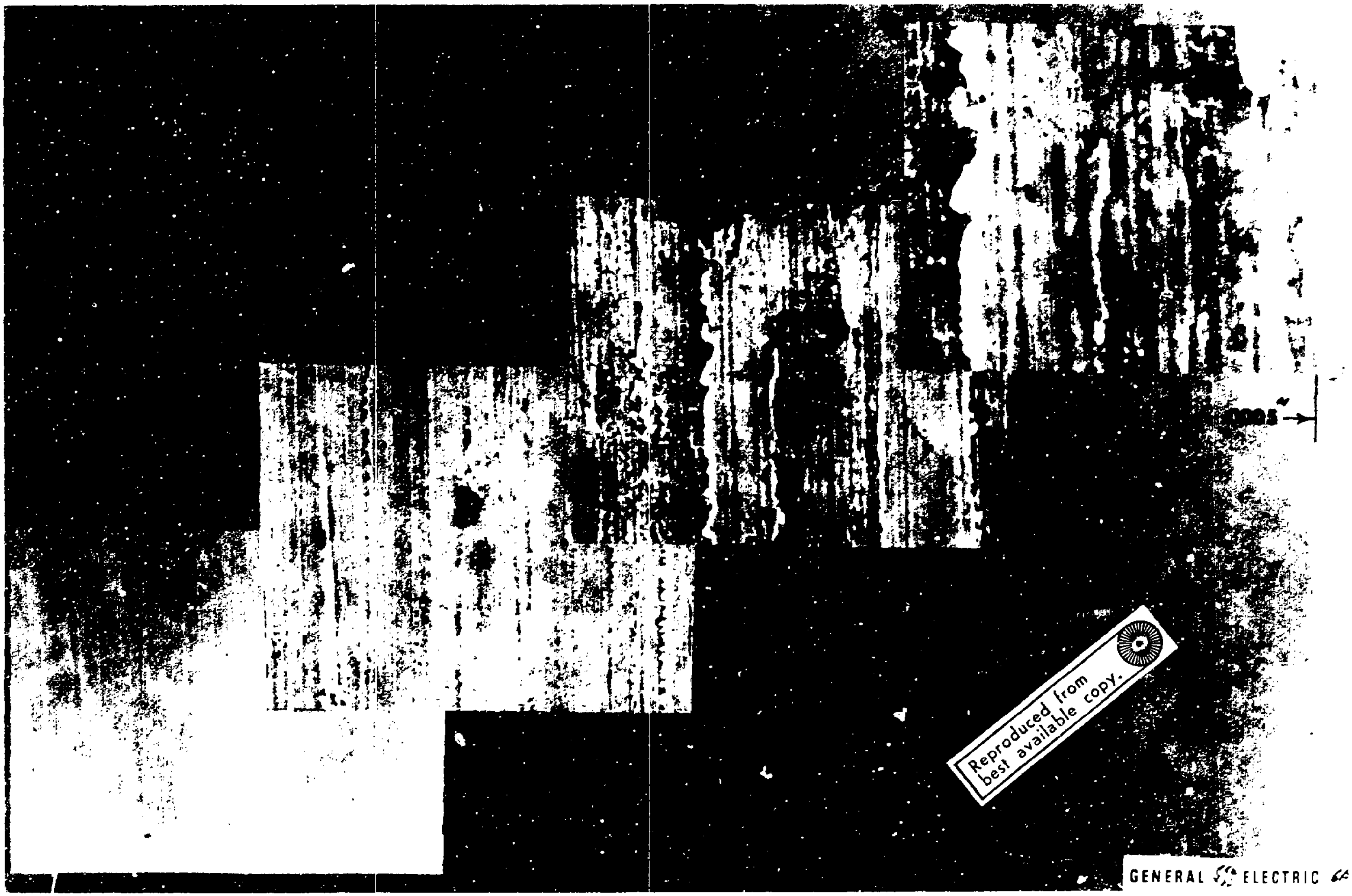


Figure 155
SCANNING ELECTRON PHOTOMICROGRAPHS:
ABUSIVE GRINDING - AF95

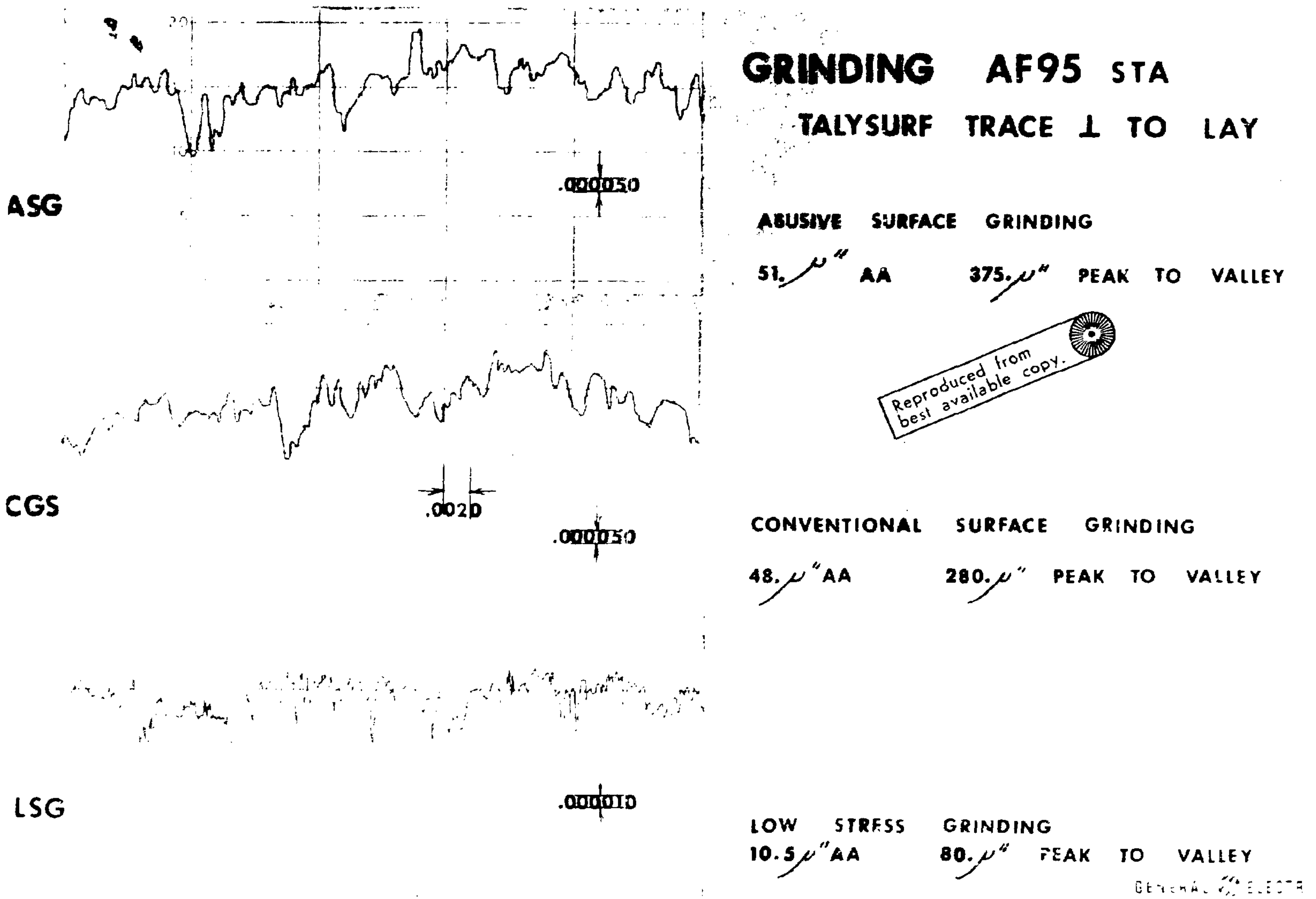


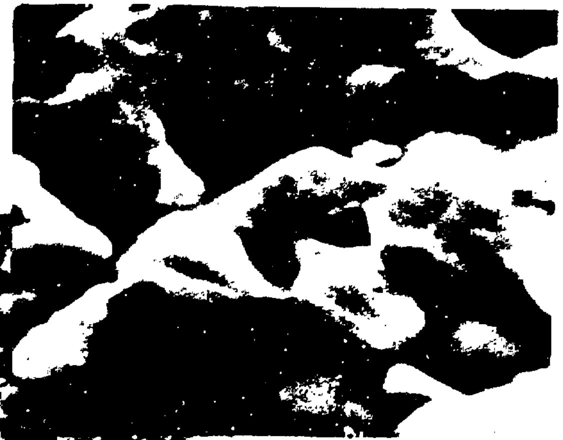
Figure 156
SCANNING ELECTRON PHOTOMICROGRAPHS:
TALYSURF TRACE, SURFACE GROUND -AF95

E C M (FINISHING) 6-6-2 TI

S E M AT 45°

TYPICAL FINISHING OR STANDARD PARAMETERS

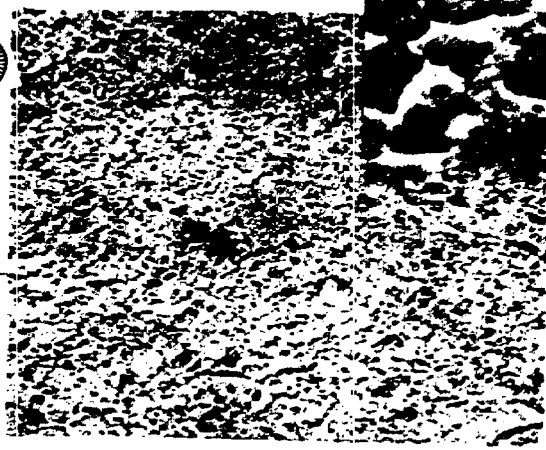
VOLTS	13
AMPS/SQ. IN.	370
FEED RATE	.045 "/MIN
GAP	.010 "
ELECTOLYTE – TYPE	1 #/GAL – NA CL
– TEMP.	100° F
– PRESS. IN	200 PSIG
– PRESS. OUT	40 PSIG
CATHODE	BRASS



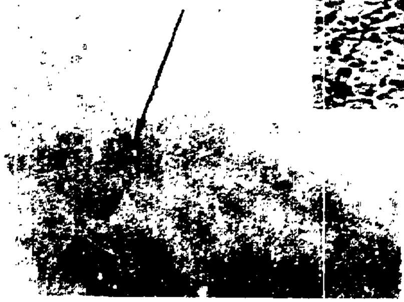
6125 X

TYPICAL AREA

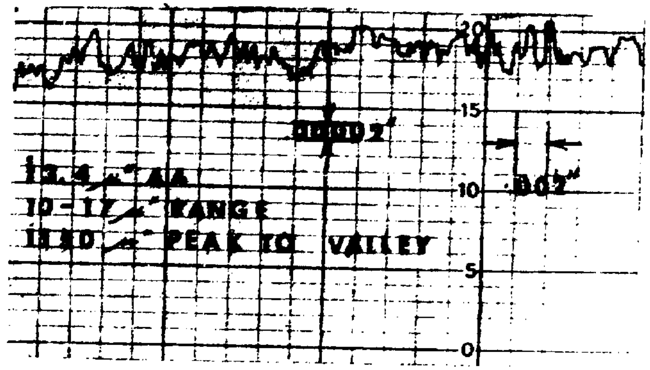
2470 X



250 X



25 X



TALYSURF TRACE

GENERAL ELECTRIC

Figure 157
SCANNING ELECTRON PHOTOMICROGRAPHS AND TALYSURF TRACE:
ECM (FINISHING) - TI-6Al-6V-2Sn

E C M (ROUGHING) 6-6-2 TI

S E M AT 45°

TYPICAL ROUGHING OR OFF STANDARD PARAMETERS

VOLTS		3
AMPS/SQ.IN		5
FEED RATE		DWELL
GAP		.040"
ELECTROLYTE	–TYPE	1 #/GAL–NA CL
	–TEMP.	100° F
	–PRESS. IN	200 PSIG
	–PRESS. OUT	40 PSIG
CATHODE		BRASS

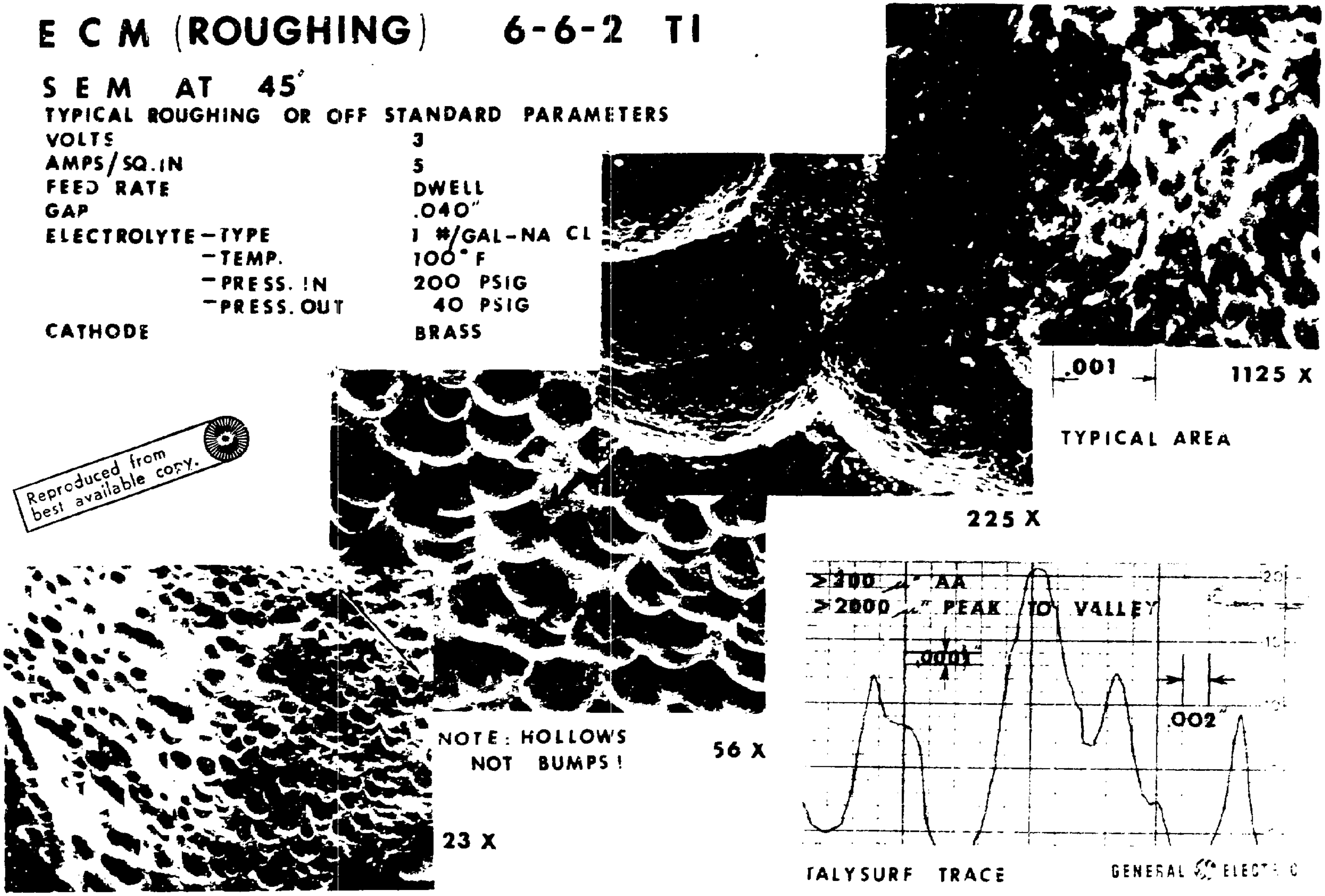


Figure 158
SCANNING ELECTRON PHOTOMICROGRAPHS AND TALYSURF TRACE:
ECM (ROUGHING) - TI-6Al-6V-2Sn

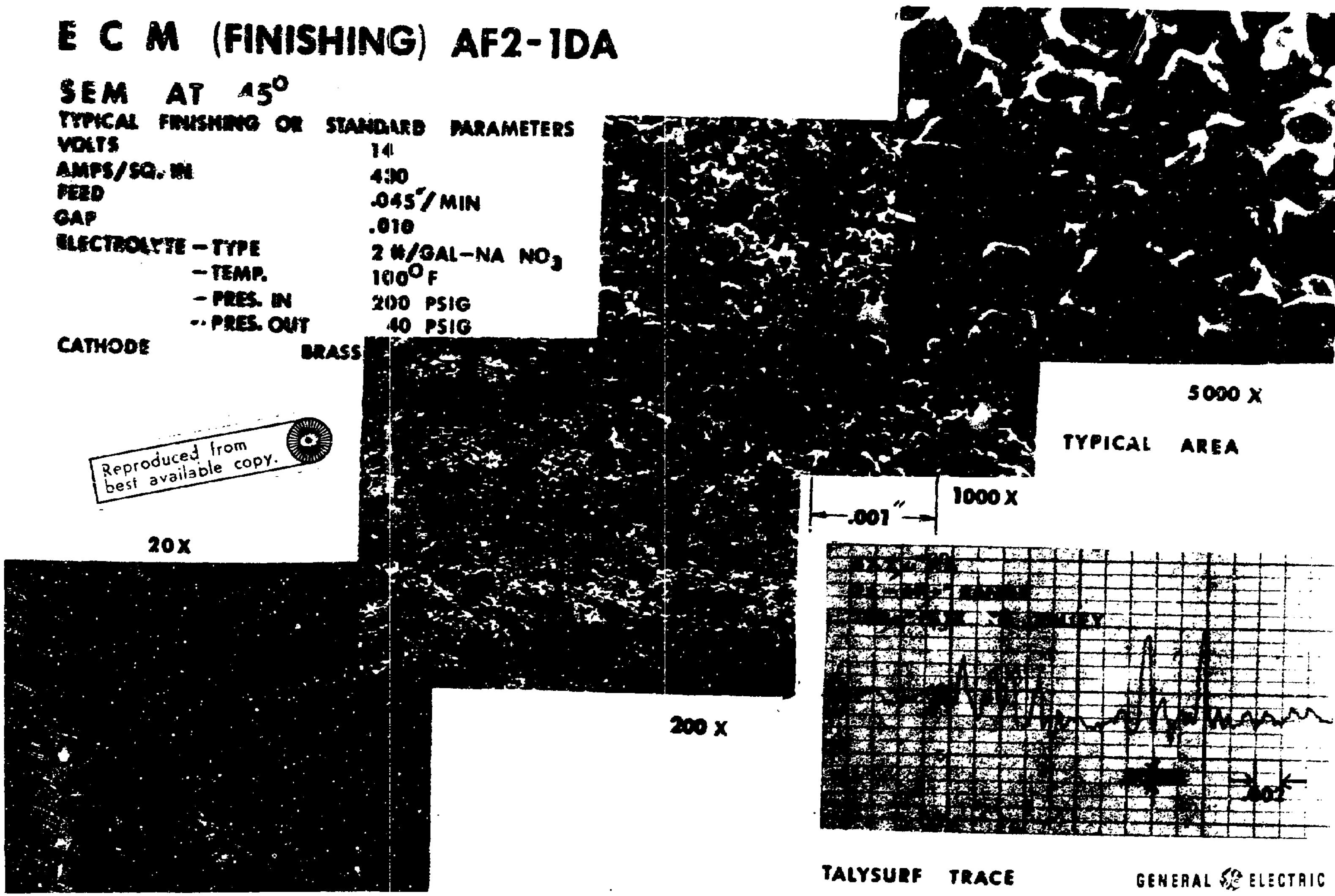
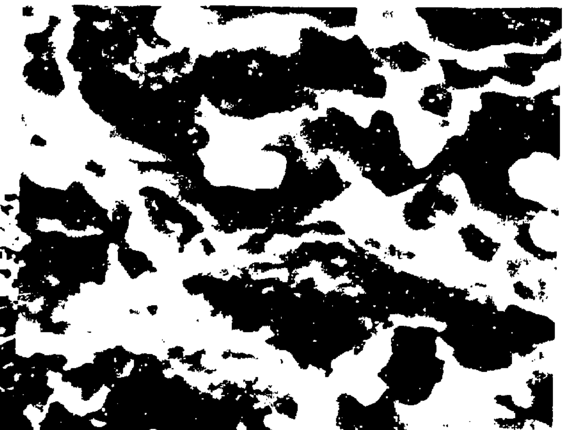


Figure 159
SCANNING ELECTRON PHOTOMICROGRAPHS AND TALYSURF TRACE:
ECM (FINISHING) - AF2-1DA

E C M (ROUGHING) AF2 - 1DA

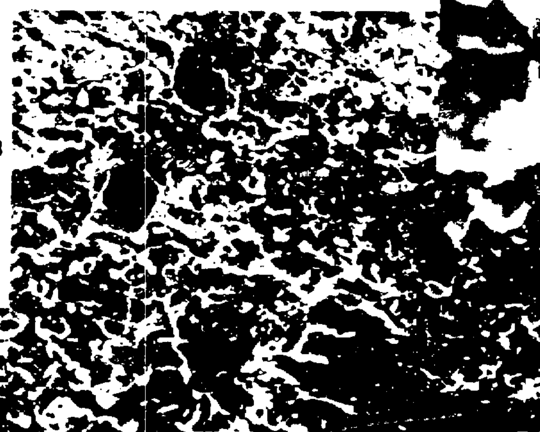
SEM AT 45°

TYPICAL ROUGHING OR OFF STANDARD PARAMETERS	
VOLTS	3
AMPS/SQ. IN	5
FEED	DWELL
GAP	.040″
ELECTROLYTE – TYPE	2 #/GAL – NA NO_3
– TEMP	100°F
– PRES. IN	200 PSIG
– PRES. OUT	40 PSIG
CATHODE	BRASS



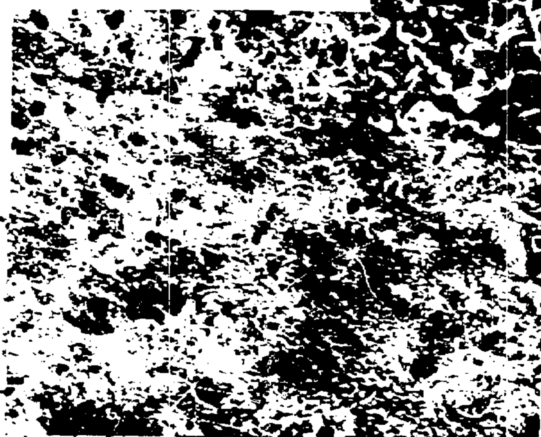
4500 X

TYPICAL AREA

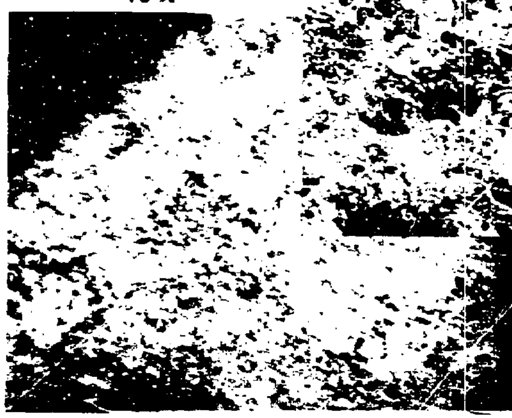


← .001″ →

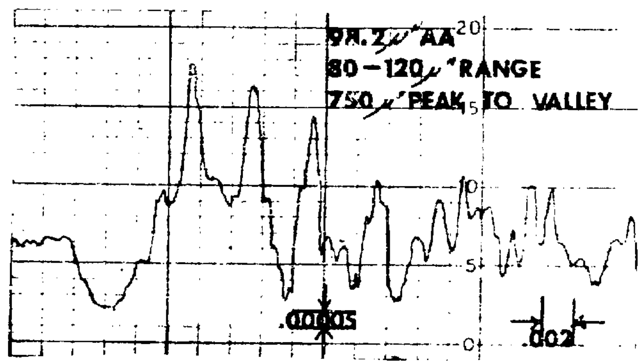
900 X



180 X



18 X



TALYSURF TRACE

GENERAL ELECTRIC

Figure 160

SCANNING ELECTRON PHOTOMICROGRAPHS AND TALYSURF TRACE: ECM (ROUGHING) - AF2-1DA

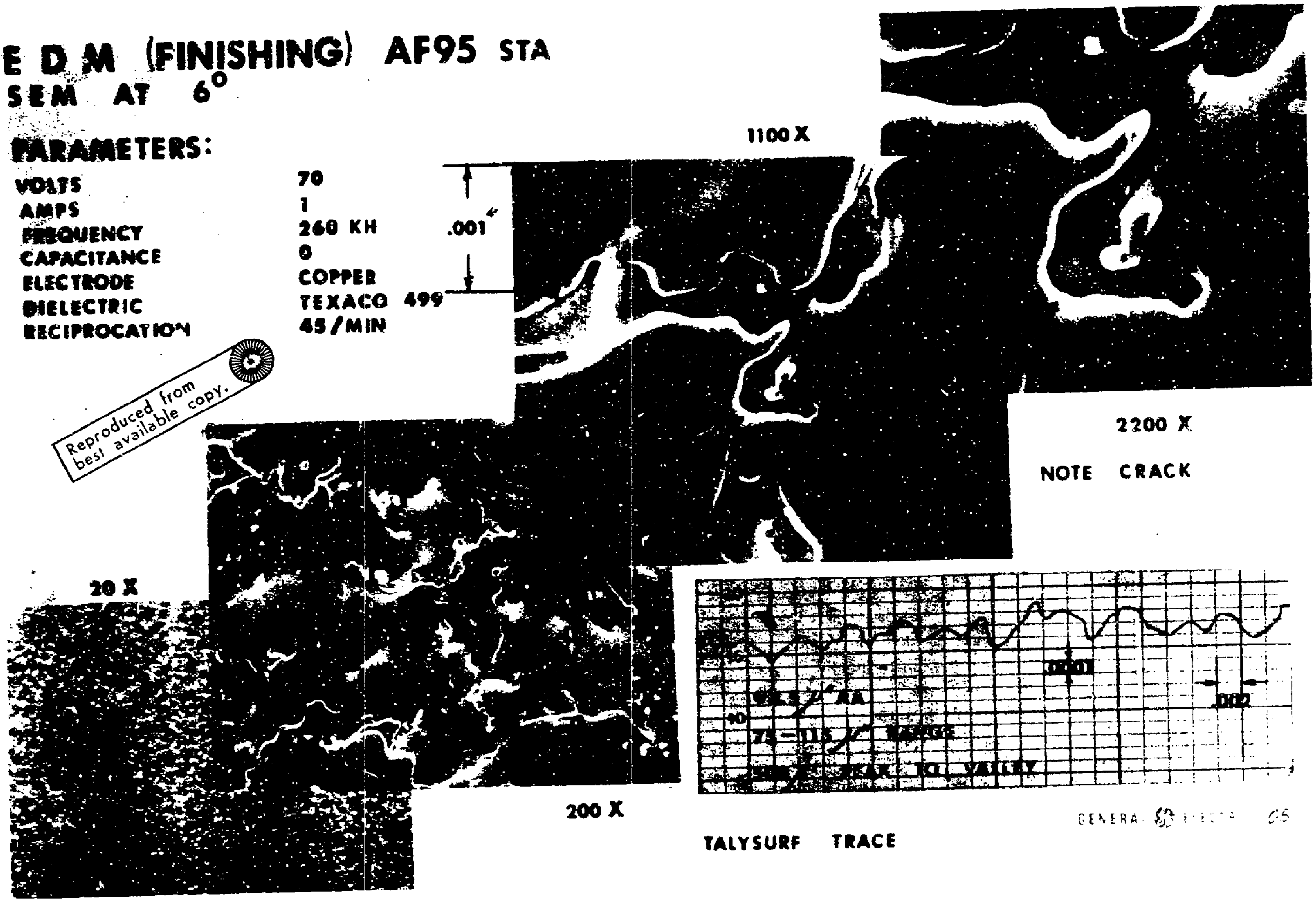
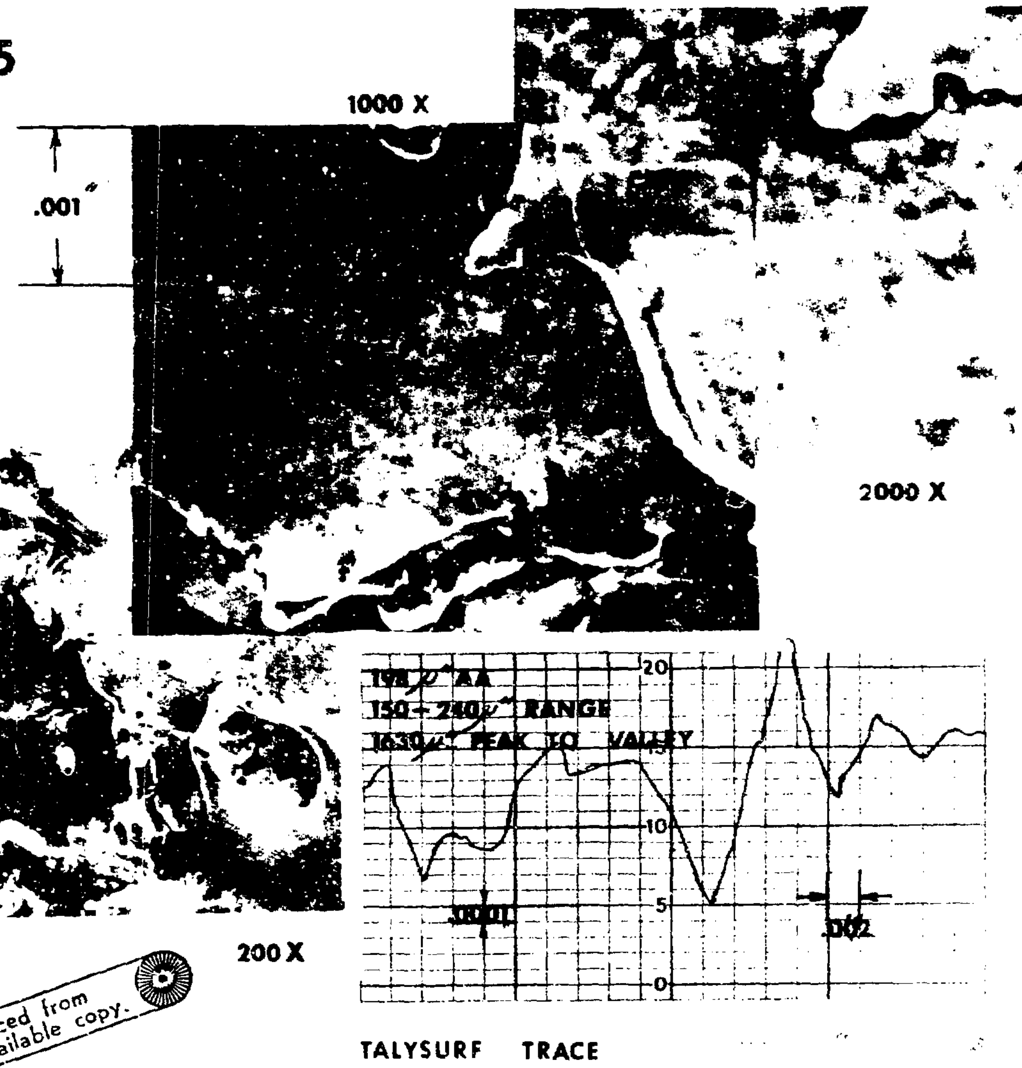


Figure 161
SCANNING ELECTRON PHOTOMICROGRAPHS AND TALYSURF TRACE:
EDM (FINISHING) - AF95

E D M **AF 95**
ROUGHING **STA**
SEM AT 6°
PARAMETERS:

VOLTS	80
AMPS	4 – 5
FREQUENCY	16 KH
CAPACITANCE	2 MFD
ELECTRODE	COPPER
DIELECTRIC	TEXACO 499
RECIPROCATION	45/MIN



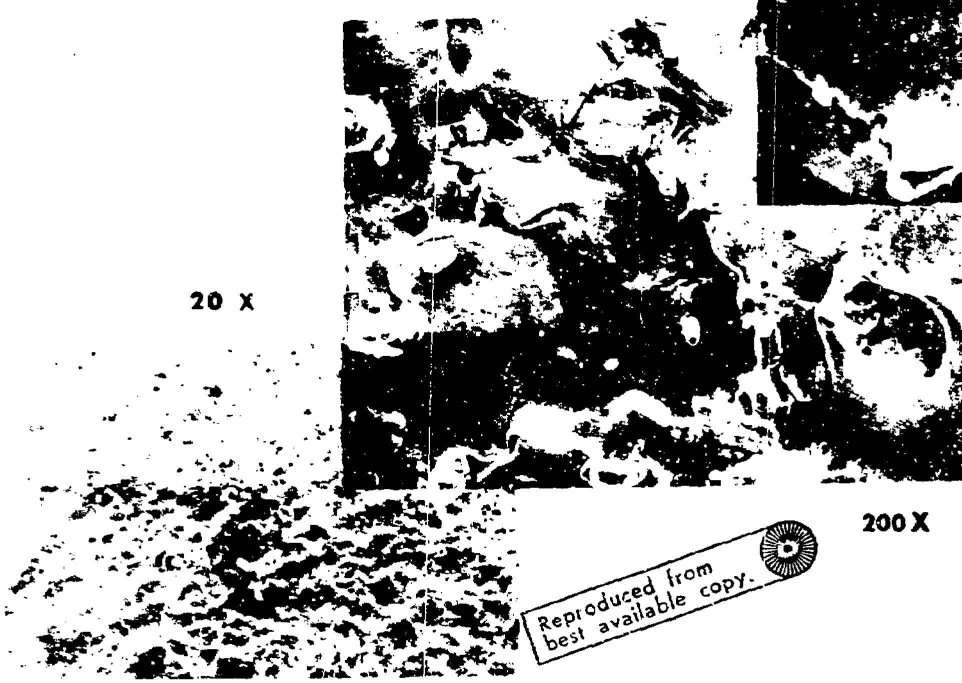


Figure 162
SCANNING ELECTRON PHOTOMICROGRAPHS AND TALYSURF TRACE:
EDM (ROUGHING) - AF95

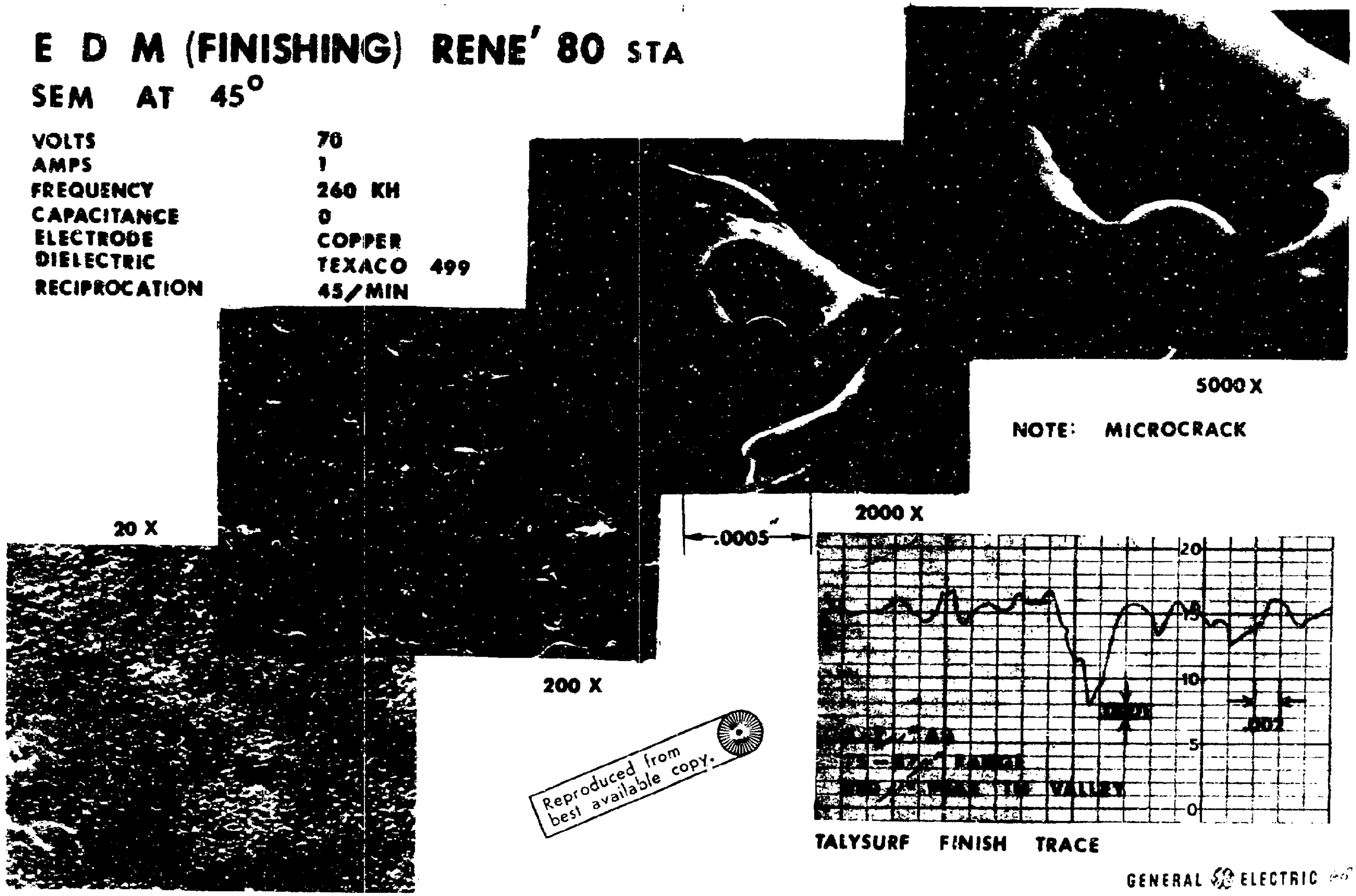


Figure 163

SCANNING ELECTRON PHOTOMICROGRAPHS AND TALYSURF TRACE: EDM (FINISHING) - RENE' 80

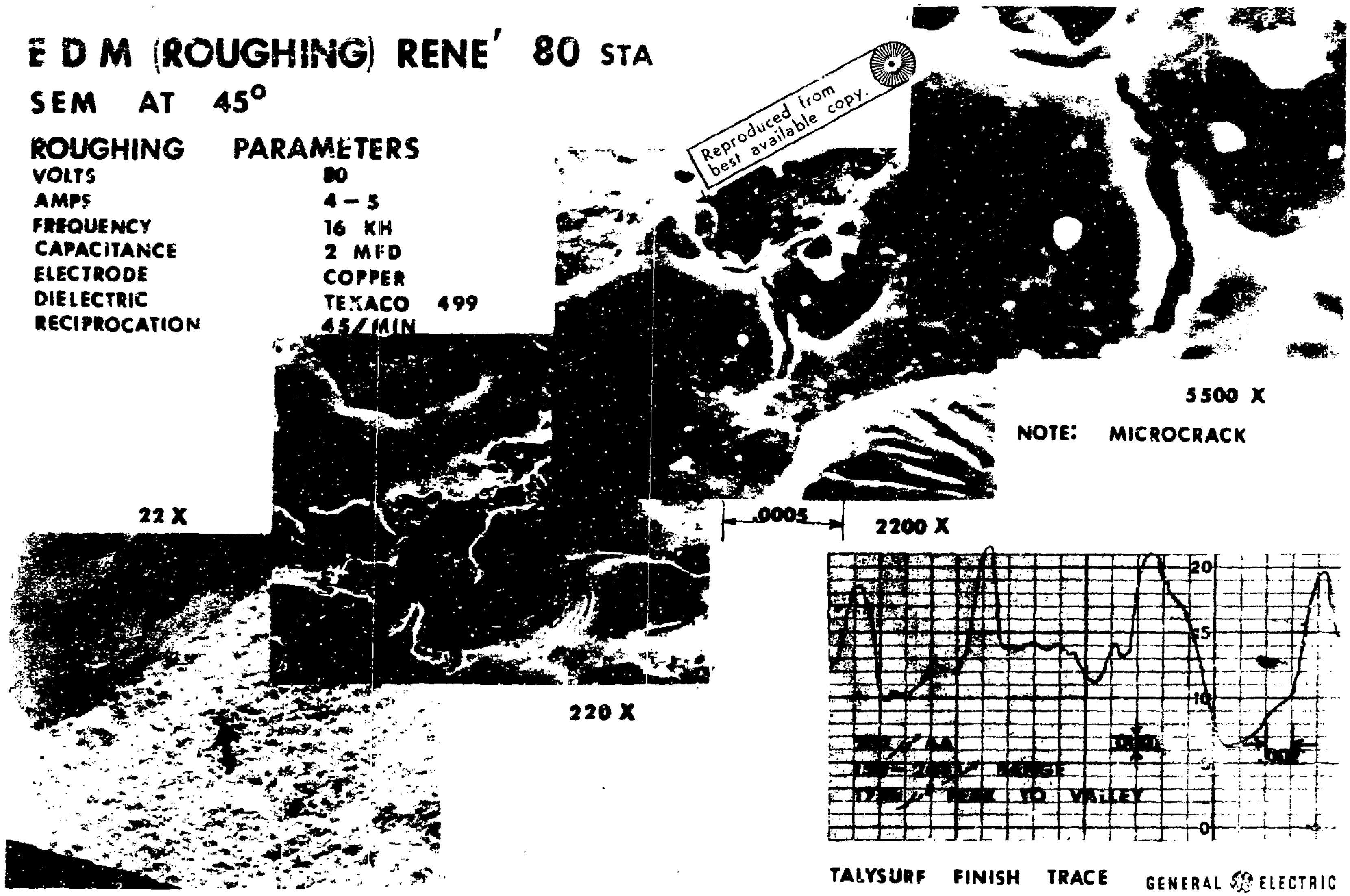


Figure 164
SCANNING ELECTRON PHOTOMICROGRAPHS AND TALYSURF TRACE:
EDM (ROUGHING) - RENE' 80

TABLE I

GENERAL MACHINING CONDITIONS USED FOR MANUFACTURING SPECIMENS ON OTHER THAN TEST CUT SURFACES

MILLING	Titanium Alloys*	Steels*	Inconel 718	AF95 AF2-1DA Rene'80
Cutter Diameter, in.:	2-3/4	2-1/2	1-3/4	2-3/4
Tool Material:	C-2(883)Carbide	M2	M42	C-2(883)Carbide
Feed, in./tooth:	.006	.004	.002	.008
Cutting Speed, ft./min.:	100	33	15	45
Tool Wear (maximum):	.006	.010	.010	.006
Cutter:	Single Tooth Fly	10 Tooth Shell Mill	10 Tooth Shell Mill	Single Tooth Fly
Fluid:	Dry	Cutmax 568 and Factoil 39 (1:1)	Cutmax and Factoil 39 (1:1)	Dry

GRINDING	Titanium Alloys*	Steels and Nickel-Base Alloys*
Grinding Wheel:	39C60J8VK	32A46G10LV
Wheel Speed, ft./min.:	3100	3100
Depth of Grind, in.:	.010	.010
Down Feed, in./pass:	First: .008 in. at .0005 in./pass Next: .0008 in. at .0004 in./pass Last: .0012 in. at .0002 in./pass	Same as Titanium Alloys
Cross Feed, in./pass:	.050	.050
Table Speed, ft./min.:	40	40
Grinding Fluid:	KNO_2(1:20)	Threadkut and Factoil 39 (1:1)

*Titanium alloys include: Ti-6Al-4V, Ti-6Al-6V-2Sn, Ti-6Al-2Sn-4Zr-2Mo
Steels include: 4340, 4340 Modified, 18% Nickel Grade 300 Marage
Nickel-Base alloys include: Inconel 718, AF95, AF2-1DA, Rene' 80

TABLE II

SURFACE GRINDING CONDITIONS
USED FOR MAKING TEST CUTS ON SPECIMENS

	Steels			Titanium Alloys			Nickel Base Alloys		
	Gentle	Conv.	Abusive	Gentle	Conv.	Abusive	Gentle	Conv.	Abusive
Grinding Wheel	A46HV	A46KV	A46MV	C60HV	C60KV	A46MV	A46HV	A46KV	A46MV
Wheel Speed ft./min.	2000	6000	6000	2000	6000	6000	2000	6000	6000
Downfeed in./pass	LS*	.001	.002	LS*	.001	.002	LS*	.001	.002
Crossfeed in./pass	.050	.050	.050	.050	.050	.050	.050	.050	.050
Table Speed ft./min.	40	40	40	40	40	40	40	40	40
Grinding Fluid	Sulf. Oil	Soluble Oil	Dry	KNO2 1:20	Chem. Emul.	Dry	Sulf. Oil	Soluble Oil	Dry
Depth of Grind (in.)	.010	.010	.010	.010	.010	.010	.010	.010	.010
No. of Wheel Dressing Passes/ depth per pass	5/.001 2 spark-outs	5/.001 2/.0005 5/.0002 4 spark-outs	5/.001 2/.0005 5/.0002 4 spark-outs	5/.001 2 spark-outs	5/.001 2/.0005 5/.0002 4 spark-outs	5/.001 2/.0005 5/.0002 4 spark-outs	5/.001 2 spark-outs	5/.001 2/.0005 5/.0002 4 spark-outs	5/.001 2/.0005 5/.0002 4 spark-outs
Diamond Traverse Rate:	1"/7 sec.	1"/7 sec.	1"/21 sec.	1"/7 sec.	1"/7 sec.	1"/21 sec.	1"/7 sec.	1"/7 sec.	1"/21 sec

Grinding Machine: Norton 8 in. by 24 in. hydraulic surface grinder

*Steels include: 4340, 4340 modified, and 18% Nickel Grade 300 Marage
Titanium include: Titanium 6Al-4V, Titanium 6Al-6V-2Sn, and Titanium 6Al-2Sn-4Zr-2Mo
Nickel Base include: Inconel 718, AF95, AF2-1DA, and AF80

TABLE III

HAND SANDING CONDITIONS
USED FOR MAKING TEST CUTS ON SPECIMENS

	Gentle		Abusive
	Steel Alloys*	Titanium Alloys*	All Alloys
Sanding Disc	Al_2O_3	Al_2O_3	Al_2O_3
Disc Condition	New	New	Worn
Grit Size	240	240	120
Cutting Speed, rev. /min.	4500	2000	6000
Applied Pressure	Light	Light	Heavy
Cutting Fluid	Hocut 237(1:50)	Hocut 237(1:50)	Dry

*Materials Used In Hand Sanding

Steel Alloys: 4340 Modified
18% Nickel Grade 300 Maraging Steel
Titanium Alloys: Ti-6Al-6V-2Sn

TABLE IV

END MILLING - END CUTTING CONDITIONS USED FOR MAKING TEST CUTS ON SPECIMENS

Cutter: 4" Dia., 5 Tooth, 45° Corner Angle, 5° Relief
Depth of Cut: .030"
Width of Cut: 2.0" on High Cycle Fatigue (Fig. 7)
1.0" on Stress Corrosion (Fig. 11)
.75" on Residual Stress (Fig. 6)

Cutting Fluid: Dry
℄ of Cutter on ℄ of Specimen

	4340		4340 Mod.		18% Nickel Grade 300 Marage	
	Gentle	Abusive	Gentle	Abusive	Gentle	Abusive
Carbide	C-6(370)	C-6(370)	C-2(883)	C-2(883)	C-2(883)	C-2(883)
Axial Rake	-5°	-5°	-5°	-5°	-5°	-5°
Radial Rake	-5°	-5°	-5°	-5°	-5°	-5°
End Cutting Edge Angle	5°	5°	0°	0°	2°	2°
Cutting Speed, ft./min.	100	175	50	70	130	160
Feed, in./tooth	.006	.010	.008	.010	.0035	.0035
Tool Wear, in.	0-.004	.030	0-.004	.030	0-.004	.030

TABLE V

END MILLING - PERIPHERAL CUTTING CONDITIONS USED FOR MAKING TEST CUTS ON SPECIMENS

Cutter: 4" Dia., 6" long, 12 Tooth, C-2(883) Carbide
Axial Rake: 15°
Radial Rake: 0°
Relief: 10°
Feed: .004 in. /tooth
Depth of Cut: .030"
Width of Cut: 2.0" on High Cycle Fatigue (Fig.7)
1.5" on Low Cycle Fatigue (Fig. 9)
1.0" on Stress Corrosion (Fig.11)
.75" on Residual Stress (Fig. 6)

	Gentle	Abusive
Cutting Speed, ft. /min.	100	150
Cutting Fluid:	Hocut 237(1:30)	Dry
Tool Wear, in.	0-.004	.015-.020

TABLE VI

TURNING CONDITIONS USED FOR MAKING TEST CUTS ON SPECIMENS

Tool: C-2(883) Carbide, .030" Nose Radius
Depth of Cut: .010"
Cutting Fluid: Staysol 77 (1:20)

	Inconel 718		AF95	
	Gentle	Abusive	Gentle	Abusive
Back Rake:	-5°	-5°	-7°	-7°
Side Rake:	0°	0°	0°	0°
Side Cutting Edge Angle:	30°	30°	45°	45°
End Cutting Edge Angle:	60°	60°	45°	45°
Relief:	10°	10°	7°	7°
Cutting Speed, ft./min.:	35	35	10	10
Feed, in./rev.:	.007	.007	.006	.006
Tool Wearland, in.:	0-.004	.030	0-.004	.030

TABLE VII

DRILLING CONDITIONS USED FOR MAKING TEST CUTS ON SPECIMENS

	4340 Modified	18% Nickel Grade 300 Maraging Steel
Cutting Speed, ft. /min.	15	25
Feed, in. /rev.	.0005	.001
Drill Material	T-15	T-15
Drill Dia., in.	.250	.250
Depth of Hole, in.	.400 thru	.400 thru
Point Angle	118°	118°
Point Type	plain	plain
Relief	10°	10°
Cutting Fluid	Chlorinated Oil	Chlorinated Oil
Wearland, in.	.000 .008 .030	.000 .008 .030

TABLE VIII

EDM CONDITIONS USED FOR MAKING TEST CUTS ON SPECIMENS

Mode: Reciprocating, 45 strokes/min.
Dialectric: Texaco 499
Electrode Material: Copper

Roughing (Off Standard) Condition

Voltage (Volts)	Frequency (Kilo hertz)	Current (Amperes)	Capacitance (Microfarads)	Depth of Cut (Inches)
72-74	8	15	2	First .032-.035"
80	16	4-5	2	Last .010"

Finishing (Standard) Condition

Voltage (Volts)	Frequency (Kilo hertz)	Current (Amperes)	Capacitance (Microfarads)	Depth of Cut (Inches)
70	8	10	2	First .027-.030"
70	16	8	1	Next .010"
70	65	6	0.5	Next .003"
70	250	1	0	Last .002"

TABLE IX

ECM CONDITIONS USED FOR MAKING TEST CUTS ON SPECIMENS

STANDARD CONDITIONS	AF 95	Rene' 80	AF2-1DA	Ti-6-6-2	In-718	4340	Marage 300
Volts	14	10	1[illegible]	13	17	10	10
Amps/sq. in.	400-500	200-350	430	370	425	300	300
Feed, in./min.	.045-.050	.045-.050	.045	.045	.045	.045	.045
Gap, in.	.010	.010	.010	.010	.010	.010	.010
Electrolyte - Type	2#/gal. $NaNO_3$	1#/gal. NaCl	2#/gal. $NaNO_3$	1#/gal. NaCl	1#/gal. NaCl	1#/gal-NaCl 2#/gal-$NaNO_3$	1#/gal. -NaCl 2#/gal. -$NaNO_3$
- Temp °F	100	100	100	100	100	100	100
Inlet pressure, psig	200	250	200	200	240	300	200
Outlet pressure, psig	40	35	40	40	40	70	40
Cathode material	Brass	Brass	Brass	Brass	Brass	Brass	Brass

OFF-STANDARD CONDITIONS	AF 95	Rene' 80	AF2-1DA	Ti-6-6-2	In-718	4340	Marage 300
Volts	35	3	3	3	3	3	3
Amps/sq. in.	150	10	5	5	5	5	5
Feed, in./min.	Dwell* 60 secs.	Dwell* 30 secs.	Dwell* 120 secs.	Dwell* 165 secs.	Dwell* 180 secs.	Dwell* 30 secs.	Dwell* 30 secs.
Gap, in.	.254	.017	.040	.040	.045	.040	.040
Electrolyte - Type	2#/gal. $NaNO_3$	1#/gal. NaCl	2#/gal. $NaNO_3$	1#/gal. NaCl	1#/gal. NaCl	1#/gal-NaCl 2#/gal-NaCl	1#/gal - NaCl 2#/gal -$NaNO_3$
- Temp °F	100	100	100	100	85	100	100
Inlet pressure, psig	200	40	200	200	240	200	200
Outlet pressure, psig	90	30	40	40	40	40	40

Note: * The dwell cycle is used at low voltages to obtain low current density area associated with side wall conditions.

TABLE X

TEST CUT CONDITIONS

GENTLE SURFACE GRINDING PROCEDURES USED ON AISI 4340 (50 R_c) FOR THE SURFACE FINISH STUDY

Surface Finish, μ in. AA (perpendicular to lay)	8-11	58-65	127-128
Grinding Wheel	A46HV	A46HV	A46HV
Wheel Speed, ft./min.	2000	2000	2000
Down Feed, in./pass	"LS"*	"LS"*	"LS"*
Cross Feed, in./pass	.050	.100	.100
Table Speed, ft./min.	40	40	40
Depth of Grind	.010"	.010"	.010"
Grinding Fluid	Sulfurized Oil	Sulfurized Oil	Sulfurized Oil
Wheel Width, in.	1.0	1/2	1/2
No. of Wheel Dressing passes/depth per pass	5/.001 2/.0005 5/.0002 4 sparkouts	6/.001 2 sparkouts	6/.001 No sparkouts
Diamond Traverse Rate	1" in 21 sec.	1" in 5 sec.	1" in 2 sec.

Grinding Machine: Norton 8 in. by 24 in. hydraulic surface grinder.

*LS: Low Stress Down Feed: First: .008 in. at .0005 in./pass
Next: .0008 in. at .0004 in./pass
Last: .0012 in. at .0002 in./pass

TABLE X (cont.)

TEST CUT CONDITIONS

ABUSIVE SURFACE GRINDING PROCEDURES USED ON AISI 4340 (50 R_c) FOR THE SURFACE FINISH STUDY

Surface Finish, u in. AA (perpendicular to lay)	29	64	97
Grinding Wheel	A46MV	A46MV	A46MV
Wheel Speed, ft. /min.	6000	6000	6000
Down Feed, in. /pass	.002	.002	.002
Cross Feed, in. /pass	.050	.100	.100
Table Speed, ft. /min.	40	40	60
Depth of Grind:	.010"	.010"	.010"
Grinding Fluid	Dry	Dry	Dry
Wheel Width, in.	1/2	1/4	1/4
No. of Wheel Dressing passes/depth per pass	5/.001 2/.0005 5/.0002 4 sparkouts	6/.001 2 sparkouts	6/.001 No sparkouts
Diamond Traverse Rate	1" in 21 sec.	1" in 7 sec.	1" in 3.5 sec.

Grinding Machine: Norton 8 in. by 24 in. hydraulic surface grinder.

TABLE X (cont.)

TEST CUT CONDITIONS

GENTLE TURNING PROCEDURES USED ON INCONEL 718 FOR THE SURFACE FINISH STUDY

Conditions Common to All Gentle Turning

Tool Material:	(C-2) 883 Brazed Tool
Back Rake:	5° Neg.
Side Rake:	0
Side Cutting Edge Angle:	30°
Edge Cutting Edge Angle:	60°
Relief:	10°
Depth of Cut, in.:	.010
Cutting Fluid:	Soluble Oil (1:20)
Tool Wearland, in.:	0-.004
Cutting Speed, ft./min.	35

Conditions Which Varied With Surface Finish

	25 AA	58 AA	118 AA
Nose Radius, in.:	.050	.031	.023
Feed, in./rev.	.007	.007	.012

TABLE X (cont.)

TEST CUT CONDITIONS

ABUSIVE TURNING PROCEDURES USED ON INCONEL 718 FOR THE SURFACE FINISH STUDY

Tool Material:	(C-2) 883 Brazed Tool
Back Rake:	5° Neg.
Side Rake:	0
Side Cutting Edge Angle:	30°
Edge Cutting Edge Angle:	60°
Relief:	10°
Nose Radius, in.:	.030
Depth ot Cut, in.:	.010
Cutting Fluid:	Soluble Oil (1:20)
Tool Wearland, in.:	.030
Cutting Speed, ft./min.	35
Feed, in./rev.	.007

TABLE X (cont.)

TEST CUT CONDITIONS

GENTLE END MILLING (END CUTTING) PROCEDURES USED ON Ti-6-6-2 FOR THE SURFACE FINISH STUDY

Cutter: 4" dia., single tooth, C-2 (883) Carbide
Axial Rake, (AR): +5°
Radial Rake, (RR): 0
Corner Angle (CA): 45°
Clearance: 10°

Cutting Speed: 100 ft./min.
Feed: .004 in./tooth
Depth of Cut: .010 in.
Width of Cut: 2.0 in. on High Cycle Fatigue
.750 in. on Residual Stress
Cutting Fluid: #237 Hocut (30:1) Spray Mist
Tool Wear: 0-.004 in.

℄ of Cutter on ℄ of Specimen

Conditions Which Varied With Surface Finish

	13 AA	55 AA	125 AA
End Cutting Edge Angle,(ECEA):	1°	5°	10°

TABLE XI

POST TREATMENT CONDITIONS USED ON TEST CUT SURFACES

SHOT PEENING CONDITIONS:

	Ti-6Al-6V-2Sn	Inconel 718	AF95	Rene' 80
Shot Size	S170	S110	S110	S110
Intensity	.006 - .008 A_2	.006-.008 A_2	.004-.006 A_2	.004-.006 A_2
Coverage	300%	300%	300%	300%
Shot Hardness	45-50 R_c	50-55 R_c	50-55 R_c	50-55 R_c

TABLE XII

SUMMARY OF HIGH CYCLE FATIGUE TEST DATA FOR AISI 4340 ALLOY QUENCHED AND TEMPERED (50 R_c)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
GENTLE END MILLING (END CUTTING)			
22-31	130.0	47	Failure
22-32	110.0	159	Failure
22-38	100.0	220	Failure
22-33	90.0	263	Failure
22-37	90.0	12,877	Runout
22-D	85.0	14,836	Runout
22-35	80.0	10,064	Runout
22-34	70.0	10,238	Runout
ABUSIVE END MILLING (END CUTTING)			
22-46	90.0	130	Failure
22-39	80.0	186	Failure
22-42	75.0	2,071	Failure
22-45	75.0	12,842	Runout
22-41	70.0	10,039	Runout
22-43	70.0	688	Failure
22-44	70.0	10,233	Runout
22-40	60.0	14,638	Runout

TABLE XIII

SUMMARY OF LOW CYCLE FATIGUE TEST DATA FOR AISI 4340 ALLOY QUENCHED AND TEMPERED (50 R_C)

Specimen No.	Pseudo Stress (ksi)	Fatigue Cycles
GENTLE SURFACE GRINDING		
21-5	290	1,714
11-17	256	2,455
21-4	240	3,613
11-15	200	10,469
21-6	160	26,836
ABUSIVE SURFACE GRINDING		
21-9	290	1,147
21-10	240	2,911
21-7	200	6,871
21-11	170	11,600
21-8	140	21,420

TABLE XIV

SUMMARY OF HIGH CYCLE FATIGUE TEST DATA
FOR 4340 MODIFIED ALLOY QUENCHED AND TEMPERED (53 R_c, 285 KSI)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
GENTLE SURFACE GRINDING			
23-1	160.0	49	Failure
23-2	140.0	291	Failure
23-3	130.0	3,702	Failure
23-5	130.0	1,020	Failure
23-4	125.0	10,053	Runout
23-6	125.0	3,554	Failure
23-8*	125.0	706	Failure
23-7	120.0	10,303	Runout
CONVENTIONAL SURFACE GRINDING			
23-20	120.0	23	Failure
23-17	100.0	524	Failure
23-18	90.0	588	Failure
23-23	75.0	4,277	Failure
23-19	70.0	9,302	Failure
23-22	70.0	15,108	Runout
23-24	70.0	7,231	Failure
23-21	65.0	10,118	Runout
ABUSIVE SURFACE GRINDING			
23-9	100.0	46	Failure
23-10	80.0	122	Failure
23-12	70.0	3,496	Failure
23-14	70.0	8,565	Failure
23-13	65.0	12,884	Runout
23-15	65.0	6,351	Failure
23-11	60.0	14,544	Runout
23-16	60.0	10,018	Runout

*Failed at internal inclusion

TABLE XIV (continued)

SUMMARY OF HIGH CYCLE FATIGUE TEST DATA FOR 4340 MODIFIED ALLOY QUENCHED AND TEMPERED (53 R_c, 285 KSI)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
GENTLE HAND SANDING			
24-1A	125.0	1,498	Failure
24-2A	120.0	373	Failure
24-4A	115.0	2,142	Failure
24-5A	110.0	3,102	Failure
24-7A	110.0	757	Failure
24-6A	105.0	10,297	Runout
24-8A	105.0	9,800	Failure
ABUSIVE HAND SANDING			
24-16A	140.0	58	Failure
24-15A	120.0	10,020	Runout
24-13A	115.0	3,917	Failure
24-9A	110.0	549	Failure
24-14A	110.0	10,516	Runout
24-11A	105.0	12,726	Runout
24-10A	100.0	12,450	Runout

TABLE XIV (continued)

SUMMARY OF HIGH CYCLE FATIGUE TEST DATA FOR 4340 MODIFIED ALLOY QUENCHED AND TEMPERED (53 R_c, 285 KSI)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
GENTLE END MILLING (END CUTTING)			
25-6A	150.0	14	Failure
25-3A	110.0	40	Failure
25-4A	90.0	107	Failure
25-2A	75.0	162	Failure
25-1A	70.0	10,092	Runout
25-7A	70.0	397	Failure
25-8A	65.0	262	Failure
25-5A	60.0	10,264	Runout
ABUSIVE END MILLING (END CUTTING)			
25-12A	130.0	33	Failure
25-10A	100.0	78	Failure
25-A	80.0	1,447	Failure
25-11A	70.0	337	Failure
25-16A	70.0	10,135	Runout
25-15A	65.0	10,231	Runout
25-14A	60.0	10,630	Runout
25-13A	50.0	12,760	Runout

TABLE XV

SUMMARY OF HIGH CYCLE FATIGUE TEST DATA
FOR 18% NICKEL GRADE 300 MARAGING STEEL ALLOY
SOLUTION TREATED AND AGED (54 R_c)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
GENTLE SURFACE GRINDING			
28-1	158.0	40	Failure
28-2	140.0	101	Failure
28-3	120.0	876	Failure
28-4	110.0	5,403	Failure
28-6	110.0	3,378	Failure
28-8	110.0	10,222	Runout
28-5	105.0	12,558	Runout
28-7	105.0	12,918	Runout
CONVENTIONAL SURFACE GRINDING			
28-17	130.0	140	Failure
28-22	120.0	150	Failure
28-18	110.0	170	Failure
28-19	90.0	624	Failure
28-21	85.0	5,120	Failure
28-20	80.0	12,129	Runout
28-23	80.0	352	Failure
28-24	80.0	15,352	Runout
ABUSIVE SURFACE GRINDING			
28-9	120.0	43	Failure
28-10	100.0	111	Failure
28-12	90.0	9,875	Failure
28-14	90.0	2,676	Failure
28-13	85.0	10,127	Runout
28-15	85.0	356	Failure
28-16	85.0	12,266	Failure
28-11	80.0	12,506	Runout

TABLE XV (continued)

SUMMARY OF HIGH CYCLE FATIGUE TEST DATA FOR

18% NICKEL GRADE 300 MARAGING STEEL ALLOY

SOLUTION TREATED AND AGED (54 R_c)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
GENTLE HAND SANDING			
29-1	110.0	245	Failure
29-3	100.0	361	Failure
29-6	93.5	330	Failure
29-2	90.0	4,822	Failure
29-5	90.0	10,072	Runout
29-7	90.0	9,354	Failure (a)
29-4	85.0	10,379	Runout
29-8	85.0	655	Failure
ABUSIVE HAND SANDING			
29-9	100.0	674	Failure
29-10	95.0	602	Failure
29-11	90.0	5,196	Failure
29-14	90.0	2,433	Failure (a)
29-16	90.0	10,020	Runout
29-12	85.0	919	Failure
29-13	85.0	10,004	Runout
29-15	85.0	10,116	Runout

(a) Possible nick at origin

TABLE XV (continued)

SUMMARY OF HIGH CYCLE FATIGUE TEST DATA FOR 18% NICKEL GRADE 300 MARAGING STEEL ALLOY SOLUTION TREATED AND AGED (54 R_c)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
GENTLE END MILLING (END CUTTING)			
30-8	145.0	141	Failure
30-3	140.0	647	Failure
30-4	130.0	5,654	Failure
30-7	130.0	7,694	Failure
30-6	125.0	14,907	Runout
30-A	125.0	469	Failure
EX-1	120.0	10,208	Runout
ABUSIVE END MILLING (END CUTTING)			
30-12	150.0	68	Failure
30-13	140.0	71	Failure
30-14	130.0	623	Failure
30-15	125.0	926	Failure
30-11	120.0	10,260	Runout
30-16	120.0	340	Failure

TABLE XVI

SUMMARY OF LOW CYCLE FATIGUE TEST DATA FOR Ti-6Al-4V ALLOY (BETA ROLLED)

Specimen No.	Pseudo Stress (ksi)	Fatigue Cycles
GENTLE SURFACE GRINDING		
33-1	145	1,727
33-3	130	3,384
33-2	115	7,733
33-4	105	9,056
33-5	90	21,367
33-6	80	42,303
ABUSIVE SURFACE GRINDING		
33-8	140	3,430
33-7	125	3,884
33-9	100	8,369
33-10	80	16,902
33-11	70	21,639

TABLE XVI (continued)

SUMMARY OF LOW CYCLE FATIGUE TEST DATA FOR

Ti-6Al-4V ALLOY (BETA ROLLED)

Specimen No.	Pseudo Stress (ksi)	Fatigue Cycles
GENTLE END MILLING (PERIPHERAL CUTTING)		
34-14	150.0	2,459
34-17	135.0	4,489
34-15	120.0	6,966
34-16	100.0	22,547
34-25	95.0	28,876
34-13	85.0	40,477
ABUSIVE END MILLING (PERIPHERAL CUTTING)		
34-19	150.0	4,942
34-23	120.0	16,544
34-18	110.0	14,672
34-22	100.0	26,970
34-21	85.0	51,690

TABLE XVII

SUMMARY OF HIGH CYCLE FATIGUE TEST DATA FOR Ti-6Al-6V-2Sn ALLOY SOLUTION TREATED AND AGED (42 R_c)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
GENTLE SURFACE GRINDING			
35-1	120.0	18	Failure
35-2	100.0	57	Failure
35-3	90.0	206	Failure
35-4	80.0	557	Failure
35-5	70.0	2,743	Failure
35-7	70.0	373	Failure
35-6	65.0	10,273	Runout
35-8	65.0	10,320	Runout
CONVENTIONAL SURFACE GRINDING			
35-17	70.0	31	Failure
35-18	50.0	110	Failure
35-20	40.0	208	Failure
35-21	35.0	345	Failure
35-23	35.0	478	Failure
35-19	30.0	10,000	Runout
35-22	30.0	10,056	Runout
35-24	30.0	10,042	Runout
ABUSIVE SURFACE GRINDING			
35-9	80.0	17	Failure
35-10	60.0	35	Failure
35-11	40.0	117	Failure
35-13	30.0	259	Failure
35-14	25.0	233	Failure
35-16	25.0	503	Failure
35-12	20.0	10,023	Runout
35-15	20.0	10,062	Runout

TABLE XVII (continued)

SUMMARY OF HIGH CYCLE FATIGUE TEST DATA FOR Ti-6Al-6V-2Sn ALLOY SOLUTION TREATED AND AGED (42 R_c)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
GENTLE HAND SANDING			
36-1	75.0	70	Failure
36-3	75.0	5,892	Failure (a)
36-4	72.5	601	Failure
3[illegible]-2	70.0	10,041	Runout
36-5	70.0	3,810	Failure
36-8	70.0	7,044	Failure (a)
36-6	67.5	9,194	Failure
36-7	65.0	10,260	Runout
ABUSIVE HAND SANDING			
36-9	75.0	75	Failure
36-11	75.0	312	Failure
36-13	75.0	367	Failure
36-14	72.5	1,423	Failure
36-10	70.0	10,009	Failure (a)
36-12	70.0	10,680	Runout
36-15	70.0	8,879	Failure (a)
36-16	67.5	4,807	Failure (a)

(a) Possible subsurface failure.

TABLE XVII (continued)

SUMMARY OF HIGH CYCLE FATIGUE TEST DATA FOR
Ti-6Al-6V-2Sn ALLOY SOLUTION
TREATED AND AGED (42 R_c)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
GENTLE END MILLING (PERIPHERAL CUTTING)			
37-9	120.0	29	Failure
37-10	100.0	205	Failure
37-11	90.0	554	Failure
37-12	80.0	2,940	Failure
37-13	75.0	9,191	Failure
37-15	75.0	4,859	Failure
37-14	70.0	14,319	Runout
37-16	70.0	12,791	Runout
ABUSIVE END MILLING (PERIPHERAL CUTTING)			
37-26	115.0	17	Failure
37-20	100.0	19	Failure
37-21	80.0	45	Failure
37-22	60.0	859	Failure
37-23	50.0	2,861	Failure
37-25	50.0	168	Failure
37-24	45.0	10,295	Runout
37-D	45.0	7,829	Failure

TABLE XVII (continued)

SUMMARY OF HIGH CYCLE FATIGUE TEST DATA FOR FOR Ti-6Al-6V-2Sn ALLOY SOLUTION TREATED AND AGED (42 R_c)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
STANDARD ECM			
39-1	90.0	45	Failure
39-6	80.0	106	Failure
39-5	75.0	1,611	Failure
39-8	75.0	206	Failure
39-2	70.0	9,814	Failure
39-4	70.0	10,154	Runout
39-7	70.0	10,087	Runout
39-3	65.0	12,969	Runout
OFF-STANDARD ECM			
39-9	90.0	15	Failure
39-10	70.0	38	Failure
39-15	55.0	147	Failure
39-11	50.0	285	Failure
39-14	50.0	12,631	Runout
39-16	50.0	196	Failure (a)
39-13	45.0	10,147	Runout
39-12	40.0	17,486	Runout

(a) Failed at surface pit.

TABLE XVII (continued)

SUMMARY OF HIGH CYCLE FATIGUE TEST DATA FOR Ti-6Al-6V-2Sn ALLOY SOLUTION TREATED AND AGED (42 R_c)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
STANDARD ECM + PEENING			
40-2	95.0	2,774	Failure
40-4	95.0	150	Failure
40-1	90.0	3,128	Failure
40-8	90.0	371	Failure (a)
40-3	85.0	3,989	Failure (a)
40-5	85.0	6,652	Failure
40-7	85.0	10,174	Runout
40-6	80.0	10,879	Runout
OFF-STANDARD ECM + PEENING			
40-10	90.0	166	Failure (a)
40-12	90.0	160	Failure (a)
40-16	90.0	120	Failure (a)
40-13	85.0	8,762	Failure
40-14	85.0	6,376	Failure (b)
40-15	80.0	10,245	Runout
40-11	80.0	5,093	Failure (b)
40-9	70.0	10,331	Runout

(a) Edge failure.
(b) Failure origin appears to be subsurface.

TABLE XVII (cont.)

SUMMARY OF HIGH CYCLE FATIGUE TEST DATA

FOR Ti-6Al-6V-2Sn ALLOY SOLUTION

TREATED AND AGED, (42 R_c)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
GENTLE SURFACE GRINDING + PEENING			
7	100.0	190	Failure
8	95.0	2,950	Failure
9	90.0	8,296	Failure
10	85.0	7,391	Failure
11	80.0	10,010	Runout
12	85.0	10,180	Runout
ABUSIVE SURFACE GRINDING + PEENING			
19	100.0	306	Failure
20	110.0	95	Failure
21	95.0	332	Failure
22	80.0	586	Failure
23	75.0	963	Failure
24	65.0	1,807	Failure

TABLE XVIII

SUMMARY OF LOW CYCLE FATIGUE TEST DATA FOR Ti-6Al-6V-2Sn ALLOY SOLUTION TREATED & AGED (42 R_c)

Specimen No.	Pseudo Stress (ksi)	Fatigue Cycles
GENTLE END MILLING (PERIPHERAL CUTTING)		
38-4	170.0	2,045
38-5	150.0	5,423
38-3	130.0	11,711
38-A	110.0	24,448
38-6	100.0	35,424
38-B	95.0	67,653 (a)
ABUSIVE END MILLING (PERIPHERAL CUTTING)		
38-9	170.0	1,950
38-10	140.0	7,012
38-8	130.0	10,657
38-7	110.0	16,001
38-11	100.0	22,126

(a) Specimen did not fail.

TABLE XVIII (continued)

SUMMARY OF LOW CYCLE FATIGUE TEST DATA FOR Ti-6Al-6V-2Sn ALLOY SOLUTION TREATED AND AGED (42 R_c)

Specimen No.	Pseudo Stress (ksi)	Fatigue Cycles
STANDARD ECM + PEENING		
41-4	150.0	3,967
41-2	130.0	8,051
41-5	110.0	22,271
41-6	100.0	62,140 (a)
41-3	95.3	83,388 (a)
OFF-STANDARD ECM + PEENING		
41-B	150.0	1,488
41-7	130.0	3,598
41-8	110.0	6,945
41-10	90.0	70,792 (a)
41-9	80.0	62,173 (a)

(a) Specimen did not fail.

TABLE XIX

SUMMARY OF HIGH CYCLE FATIGUE TEST DATA FOR Ti-6Al-2Sn-4Zr-2Mo ALLOY SOLUTION TREATED AND AGED (36 R_c)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
GENTLE SURFACE GRINDING			
42-1	120.0	23	Failure
42-2	90.0	168	Failure
42-3	80.0	750	Failure
42-6	80.0	948	Failure
42-5	75.0	10,268	Runout
42-7	75.0	2,908	Failure
42-4	70.0	12,772	Runout
42-8	70.0	7,602	Failure
CONVENTIONAL SURFACE GRINDING			
42-17	70.0	33	Failure (a)
42-18	50.0	82	Failure (a)
42-19	25.0	560	Failure
42-24	25.0	518	Failure
42-21	20.0	1,201	Failure
42-23	20.0	10,195	Runout
42-20	15.0	10,266	Runout
42-24	15.0	10,030	Runout
ABUSIVE SURFACE GRINDING			
42-9	90.0	11	Failure (a)
42-10	60.0	24	Failure (a)
42-11	40.0	53	Failure (a)
42-13	20.0	343	Failure (a)
42-14	15.0	689	Failure
42-16	15.0	748	Failure (a)
42-12	10.0	10,059	Runout
42-15	10.0	10,122	Runout

(a) Multiple surface origins

TABLE XIX (continued)

SUMMARY OF HIGH CYCLE FATIGUE TEST DATA FOR

Ti-6Al-2Sn-4Zr-2Mo ALLOY SOLUTION

TREATED AND AGED (36 R_c)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
GENTLE END MILLING (PERIPHERAL CUTTING)			
43-1	120.0	48	Failure
43-2	100.0	301	Failure
43-4	95.0	607	Failure
43-3	90.0	10,072	Runout
43-5	90.0	596	Failure (a)
43-6	90.0	1,774	Failure (a)
43-7	90.0	1,117	Failure
43-8	85.0	7,168	Failure (a)
ABUSIVE END MILLING (PERIPHERAL CUTTING)			
43-9	120.0	24	Failure
43-12	95.0	65	Failure
43-10	85.0	126	Failure
43-11	75.0	312	Failure
43-13	70.0	169	Failure
43-14	60.0	1,652	Failure
43-15	50.0	6,993	Failure
43-16	45.0	10,109	Runout

(a) Edge failure.

TABLE XX

SUMMARY OF HIGH CYCLE FATIGUE TEST DATA FOR INCONEL 718 ALLOY SOLUTION TREATED AND AGED (44 R_c)

A. GENTLE TURNING (FACING)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
Surface Finish: 25 AA			
79-7	90.0	319	Failure
79-6	80.0	640	Failure
79-2	70.0	933	Failure
79-1X	65.0	10,257	Runout
79-4	65.0	2,592	Failure
79-8	65.0	1,512	Failure
79-5	60.0	10,229	Runout
Surface Finish: 58 AA			
79-13	90.0	314	Failure
79-11	80.0	511	Failure
79-9	70.0	4,615	Failure
79-14	70.0	9,357	Failure
79-10	65.0	10,265	Runout
79-12	65.0	10,001	Runout
79-15	65.0	2,269	Failure
79-16	60.0	10,082	Runout
Surface Finish: 118 AA			
79-22	90.0	247	Failure
79-17	80.0	417	Failure
79-18	70.0	987	Failure
79-19	65.0	1,616	Failure
79-24	65.0	10,805	Failure
79-20	60.0	5,318	Failure
79-23	60.0	12,015	Runout
79-21	55.0	12,024	Runout

TABLE XX (continued)

SUMMARY OF HIGH CYCLE FATIGUE TEST DATA
FOR INCONEL 718 ALLOY SOLUTION TREATED AND AGED (44 R_c)

B. ABUSIVE TURNING (FACING)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
Surface Finish: 76 AA			
45-14	90.0	399	Failure
45-9	80.0	650	Failure
45-10	70.0	2,013	Failure
45-11	65.0	3,015	Failure
45-13	65.0	1,713	Failure
45-16	65.0	1,704	Failure
45-12	60.0	10,000	Runout
45-15	60.0	12,449	Runout

TABLE XXI

SUMMARY OF LOW CYCLE FATIGUE TEST DATA FOR INCONEL 718 ALLOY SOLUTION TREATED AND AGED (44 R_c)

Specimen No.	Pseudo Stress (ksi)	Fatigue Cycles
GENTLE SURFACE GRINDING		
44-2	260	2,913
44-4	230	4,165
44-1	200	6,995
44-5	175	10,095
44-3	160	20,450
44-6	150	28,273
ABUSIVE SURFACE GRINDING		
44-8	275	1,536
44-7	200	4,487
44-9	160	9,729
44-10	135	16,320
44-11	95	44,958

TABLE XXI (continued)

SUMMARY OF LOW CYCLE FATIGUE TEST DATA FOR INCONEL 718 ALLOY SOLUTION TREATED AND AGED (44 R_c)

Specimen No.	Pseudo Stress (ksi)	Fatigue Cycles
GENTLE TURNING (ROOM TEMPERATURE)		
46-2	200	3, 331
46-11	185	6, 099
46-3	170	7, 155
46-5	160	10, 898
46-1	150	22, 787
46-4	140	38, 554
ABUSIVE TURNING (ROOM TEMPERATURE)		
46-6	200	2, 253
46-8	170	7, 845
46-10	160	12, 124
46-7	150	25, 650
46-9	140	45, 981

TABLE XXI (continued)

SUMMARY OF LOW CYCLE FATIGUE TEST DATA FOR INCONEL 718 ALLOY SOLUTION TREATED AND AGED (44 R_c)

Specimen No.	Pseudo Stress (ksi)	Fatigue Cycles
GENTLE TURNING (1000° F)		
47-3	200	605
47-6	160	1,154
47-2	140	2,646 (a)
47-5	120	14,312
47-1	107	31,966
47-4	100	42,070
ABUSIVE TURNING (1000° F)		
47-9	160	950
47-8	120	5,984
47-7	100	17,957
47-11	95	31,043
47-10	90	60,078 (b)

(a) Failed near thermocouple weld.

(b) Specimen did not fail.

TABLE XXI (continued)

SUMMARY OF LOW CYCLE FATIGUE TEST DATA
FOR INCONEL 718 ALLOY SOLUTION
TREATED AND AGED (44 R_c)

Specimen No.	Pseudo Stress (ksi)	Fatigue Cycles
STANDARD ECM & PEENING (ROOM TEMPERATURE)		
48-1	280	1,944
48-2	200	5,499
48-3	160	15,920
48-5	160	20,990
48-12	140	65,033 (a)
OFF-STANDARD ECM & PEENING (ROOM TEMPERATURE)		
48-9	280	1,912
48-10	200	6,195
48-11	180	17,565
48-13	160	15,425
48-14	150	40,751

(a) Specimen did not fail.

TABLE XXI (continued)

SUMMARY OF LOW CYCLE FATIGUE TEST DATA FOR INCONEL 718 ALLOY SOLUTION TREATED AND AGED (44 R_c)

Specimen No.	Pseudo Stress (ksi)	Fatigue Cycles
STANDARD ECM & PEENING (1000° F)		
49-15	175	2,967
49-7	140	7,864
49-14	130	17,090
49-11	125	29,668
49-12	122	31,032
49-13	118	56,850 (a)
OFF-STANDARD ECM & PEENING (1000° F)		
49-4	190	1,500
49-5	150	3,439
49-D	130	12,311
49-6	125	14,766
49-2	120	51,744 (a)

(a) Specimen did not fail.

TABLE XXII

SUMMARY OF HIGH CYCLE FATIGUE TEST DATA

FOR AF 95 ALLOY SOLUTION TREATED AND AGED (50 R_c)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
GENTLE SURFACE GRINDING - ROOM TEMPERATURE			
50-1	125.0	154	Failure
50-2	110.0	365	Failure
50-3	100.0	467	Failure
50-4	90.0	1,615	Failure
50-5	85.0	1,250	Failure
50-6	80.0	1,809	Failure
50-7	70.0	11,266	Runout
CONVENTIONAL SURFACE GRINDING - ROOM TEMPERATURE			
50-15	70.0	91	Failure
50-16	50.0	570	Failure
50-17	45.0	1,280	Failure
50-18	40.0	1,153	Failure
50-19	35.0	1,227	Failure
50-20	30.0	3,114	Failure
50-21	25.0	5,811	Failure
ABUSIVE SURFACE GRINDING - ROOM TEMPERATURE			
50-9	60.0	293	Failure
50-10	40.0	1,672	Failure
50-11	30.0	3,014	Failure
50-14	30.0	3,074	Failure
50-13	27.5	10,700	Runout
50-12	25.0	16,807	Runout

TABLE XXII (continued)

SUMMARY OF HIGH CYCLE FATIGUE TEST DATA

FOR AF 95 ALLOY SOLUTION TREATED AND AGED (50 R_c)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
GENTLE SURFACE GRINDING - 1000°F			
51-2	130.0	67	Failure
51-3	120.0	87	Failure
51-4	110.0	426	Failure
51-5	100.0	6,341	Failure
51-6	95.0	415	Failure (a)
51-7	95.0	13,066	Runout
51-1	90.0	12,978	Runout
ABUSIVE SURFACE GRINDING - 1000°F			
51-8	80.0	51	Failure
51-9	65.0	150	Failure
51-14	55.0	345	Failure
51-11	50.0	712	Failure
51-13	47.5	10,306	Runout
51-12	45.0	10,410	Runout
51-10	40.0	10,803	Runout

(a) Failed in tab area, at thermocouple location

TABLE XXII (continued)

SUMMARY OF HIGH CYCLE FATIGUE TEST DATA

FOR AF 95 ALLOY SOLUTION TREATED AND AGED (50 R_c)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
FINISHING EDM - ROOM TEMPERATURE			
54-10	80.0	128	Failure
54-9	70.0	213	Failure (a)
54-8	60.0	1,455	Failure
54-11	55.0	2,320	Failure
54-12	50.0	2,677	Failure
54-14	50.0	2,171	Failure
54-13	45.0	4,202	Failure
ROUGHING EDM - ROOM TEMPERATURE			
54-4	70.0	203	Failure
54-2	60.0	453	Failure
54-5	55.0	1,130	Failure (a)
54-1	50.0	2,187	Failure
54-3	45.0	3,176	Failure (a)
54-6	40.0	3,950	Failure (a)
54-7	35.0	9,247	Failure (a)

(a) Multiple Cracking

TABLE XXII (continued)

SUMMARY OF HIGH CYCLE FATIGUE TEST DATA

FOR AF 95 ALLOY SOLUTION TREATED AND AGED (50 R_c)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
STANDARD ECM & PEENING - 1000° F			
66-1	140	602	Failure
66-5	130	959	Failure
66-4	125	1,004	Failure
66-7	120	1,370	Failure
66-2	115	5,588	Failure
66-3	112	2,613	Failure
66-6	110	10,665	Runout
OFF-STANDARD ECM & PEENING - 1000° F			
66-14	140	450	Failure
66-13	130	783	Failure
66-10	120	1,323	Failure
66-12	115	3,149	Failure
66-9	110	2,194	Failure
66-11	108	10,792	Runout
66-8	105	11,023	Runout

TABLE XXII (continued)

SUMMARY OF HIGH CYCLE FATIGUE TEST DATA FOR AF 95 ALLOY SOLUTION TREATED AND AGED (50 R_c)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
STANDARD ECM - 1000° F			
62-5	120	290	Failure
62-2	110	372	Failure
62-3	100	2,841	Failure
62-6	98	3,000	Failure
62-7	97	3,405	Failure
62-4	95	11,619	Runout
62-1	80	10,235	Runout
OFF-STANDARD ECM - 1000° F			
62-13	130	100	Failure
62-11	120	124	Failure
62-8	110	1,045	Failure
62-9	100	1,272	Failure
62-12	98	2,989	Failure
62-14	97	1,192	Failure
62-10	95	10,259	Runout

TABLE XXII (continued)

SUMMARY OF HIGH CYCLE FATIGUE TEST DATA

FOR AF 95 ALLOY SOLUTION TREATED AND AGED (50 R_c)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
STANDARD ECM & PEENING - ROOM TEMPERATURE			
65-2	140	894	Failure
65-5	130	1,887	Failure
65-7	125	1,033	Failure
65-4	120	4,028	Failure
65-3	110	3,956	Failure
65-6	107.5	6,756	Failure
65-1	105	13,754	Runout
OFF-STANDARD ECM & PEENING - ROOM TEMPERATURE			
65-11	140	179	Failure
65-12	130	1,976	Failure
65-10	125	277	Failure
65-13	120	1,326	Failure
65-9	119	2,060	Failure
65-8	117.5	10,370	Runout
65-14	115	11,508	Runout

TABLE XXII (continued)

SUMMARY OF HIGH CYCLE FATIGUE TEST DATA

FOR AF 95 ALLOY SOLUTION TREATED AND AGED (50 R_c)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
STANDARD ECM - ROOM TEMPERATURE			
60-1	90.0	176	Failure
60-5	80.0	369	Failure
60-2	70.0	790	Failure
60-4	60.0	1,337	Failure
60-3	55.0	10,870	Runout
60-7	50.0	12,542	Runout
60-6	40.0	12,322	Runout
OFF-STANDARD ECM CONDITION - ROOM TEMPERATURE			
60-13	90.0	171	Failure
60-9	80.0	355	Failure
60-8	70.0	732	Failure
60-11	60.0	1,713	Failure
60-12	59.0	10,956	Runout
60-14	57.5	10,630	Runout
60-10	55.0	11,860	Runout

TABLE XXII (continued)

SUMMARY OF HIGH CYCLE FATIGUE TEST DATA FOR AF 95 ALLOY SOLUTION TREATED AND AGED (50 R_c)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
FINISHING EDM & PEENING - 1000° F			
56-3	150	163	Failure
56-5	140	336	Failure
56-7	130	382	Failure
56-1	120	579	Failure
56-6	110	2,354	Failure
56-4	100	5,290	Failure
56-2	93	10,651	Runout
ROUGHING EDM & PEENING - 1000° F			
56-10	140	44	Failure
56-8	130	402	Failure
56-9	120	500	Failure
56-12	110	1,398	Failure
56-13	100	2,396	Failure
56-11	98	552	Failure
56-14	95	10,448	Runout

TABLE XXII (continued)

SUMMARY OF HIGH CYCLE FATIGUE TEST DATA

FOR AF 95 ALLOY SOLUTION TREATED AND AGED (50 R_c)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
FINISHING EDM - 1000°F			
58-1	80.0	61	Failure
58-4	60.0	64	Failure (a)
58-6	60.0	130	Failure
58-5	55.0	110	Failure (a)
58-12	52.5	139	Failure (a)
58-9	50.0	10,660	Runout
58-7	45.0	11,040	Runout
ROUGHING EDM - 1000°F			
58-10	60.0	112	Failure
58-2	55.0	150	Failure
58-8	52.5	268	Failure
58-3	50.0	8,951	Failure
58-11	47.5	374	Failure
58-13	45.0	189	Failure
58-14	40.0	10,459	Runout

(a) Multiple cracking

TABLE XXII (continued)

SUMMARY OF HIGH CYCLE FATIGUE TEST DATA

FOR AF 95 ALLOY SOLUTION TREATED AND AGED (50 R_c)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
FINISHING EDM + PEENING - ROOM TEMPERATURE			
59-5	140.0	695	Failure
59-3	130.0	2,429	Failure
59-1	120.0	3,952	Failure
59-7	115.0	9,810	Failure
59-2	110.0	2,786	Failure (a)
59-6	107.5	13,743	Runout
59-4	105.0	10,000	Runout
ROUGHING EDM + PEENING - ROOM TEMPERATURE			
59-8	130.0	638	Failure
59-10	125.0	831	Failure
56B	120.0	2,995	Failure
56A	110.0	3,596	Failure
59-9	107.5	11,288	Runout
58B	105.0	10,000	Runout
58A	100.0	17,158	Runout

(a) Edge failure

TABLE XXIII

SUMMARY OF LOW CYCLE FATIGUE TEST DATA

FOR AF 95 ALLOY SOLUTION TREATED AND AGED (50 R_c)

Specimen No.	Pseudo Stress (ksi)	Fatigue Cycles
GENTLE TURNING - ROOM TEMPERATURE		
52-1	270.5	2,979 (a)
52-5	267.5	4,120
52-6	220.5	14,890
52-3	214	3,591
52-2	179.5	24,224
52-4	173	27,285
ABUSIVE TURNING - ROOM TEMPERATURE		
52-7	272	300 (a)
52-11	239.5	3,830 (b)
52-9	215.5	5,021 (a)
52-10	208	17,473
52-8	155	38,421

Notes:

(a) Failed in radius at end of turned surface.

(b) Failure induced by probe - specimen interaction.

TABLE XXIII (continued)

SUMMARY OF LOW CYCLE FATIGUE TEST DATA
FOR AF 95 ALLOY SOLUTION TREATED AND AGED (50 R_c)

Specimen No.	Pseudo Stress (ksi)	Fatigue Cycles
GENTLE TURNING - 1000°F		
53-5	200	3,054
53-6	185.5	5,797
53-4	176 (a)	6,088
53-3	165.5	10,116
53-1	157.5	58,093
53-2	156.5	5,150 (b)
ABUSIVE TURNING - 1000°F		
53-9	232	1,014
53-8	192	3,750
53-10	169.5	5,722 (b)
53-7	169.5	21,348
53-11	151	12,259 (c)

Notes:

(a) Specimen had 524 cycles at 153.5 ksi before stress was increased to 176 ksi.

(b) Edge failure.

(c) Failed at oxide spot on surface.

TABLE XXIII (continued)

SUMMARY OF LOW CYCLE FATIGUE TEST DATA

FOR AF 95 ALLOY SOLUTION TREATED AND AGED (50 R_c)

Specimen No.	Pseudo Stress (ksi)	Fatigue Cycles
FINISHING EDM - 1000°F		
55-3	265	141
55-6	138	2,685
55-1	132.5	2,046
55-5	120.5	6,280
55-2	99	5,991
ROUGHING EDM - 1000°F		
55-8	160.5	765
55-11	130	2,466
55-10	114	4,494
55-9	101	8,208
55-7	96.5	9,509

TABLE XXIII (continued)

SUMMARY OF LOW CYCLE FATIGUE TEST DATA

FOR AF 95 ALLOY SOLUTION TREATED AND AGED (50 R_c)

Specimen No.	Pseudo Stress (ksi)	Fatigue Cycles
FINISHING EDM & PEENING - 1000° F		
57-1	175	1,408
57-4	172	2,821
57-5	160.5	7,369
57-6	148.5	12,075
57-3	136.5	6,085 (a)
57-2	134	53,253 (b)
ROUGHING EDM & PEENING - 1000° F		
57-11	186	3,634
57-8	152.5	5,304
57-9	148.5	9,182
57-10	119	87,081 (c)
57-7	92.5	56,097 (c)

Notes:

(a) Failure at sharp corner is transition area.

(b) Edge failure.

(c) Specimen did not fail.

TABLE XXIII (continued)

SUMMARY OF LOW CYCLE FATIGUE TEST DATA

FOR AF 95 ALLOY SOLUTION TREATED AND AGED (50 R_c)

Specimen No.	Pseudo Stress (ksi)	Fatigue Cycles
STANDARD ECM - 1000°F		
61-2	161.5	3,321
61-1	136.5	7,927
61-3	127	9,706
61-B	127	15,353
61-5	126	400 (a)
61-6	99.5	77,892 (b)
OFF-STANDARD ECM - 1000°F		
61-11	165.5	3,323
61-10	137.5	14,017
61-9	132.5	6,616
61-8	118	76,318 (b)
61-7	110	57,367 (b)

(a) Thermocouple pulled loose from specimen; test discontinued.

(b) Specimen did not fail.

TABLE XXIII (continued)

SUMMARY OF LOW CYCLE FATIGUE TEST DATA

FOR AF 95 ALLOY SOLUTION TREATED AND AGED (50 R_c)

Specimen No.	Pseudo Stress (ksi)	Fatigue Cycles
STANDARD ECM & PEENING - ROOM TEMPERATURE		
63-5	263	6,888
63-4	243	9,912
63-3	240	16,553
63-1	187	21,857
63-6	176	20,254
63-2	155	52,984
OFF-STANDARD ECM & PEENING - ROOM TEMPERATURE		
63-B	234	6,239
63-A	232	3,924
63-9	213	12,532
63-11	205	36,113
63-10	187	19,986

TABLE XXIII (continued)

SUMMARY OF LOW CYCLE FATIGUE TEST DATA

FOR AF 95 ALLOY SOLUTION TREATED AND AGED (50 R_c)

Specimen No.	Pseudo Stress (ksi)	Fatigue Cycles
STANDARD ECM & PEENING - 1000°F		
64-4	224	1,230
64-1	207	2,284
64-6	176 (a)	2,518
64-2	167	67,651
64-5	159	15,028
64-3	158	8,118 (b)
OFF-STANDARD ECM & PEENING - 1000°F		
64-11	210	2,036
64-8	179	3,978
64-7	176	14,308
64-9	172 (c)	2,757
64-10	152	36,514

Notes:

(a) Specimen had 389 cycles at 152 ksi (RT) before starting test.

(b) Failed at thermocouple location.

(c) Specimen had 103 cycles at 148 ksi before stress increased to 172 ksi.

TABLE XXIV

SUMMARY OF HIGH CYCLE FATIGUE TEST DATA FOR AF2-1DA ALLOY SOLUTION TREATED AND AGED (45 R_c)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
GENTLE SURFACE GRINDING			
67-5	90.0	539	Failure
67-3	80.0	838	Failure
67-7	80.0	1,417	Failure
67-2	75.0	1,895	Failure
67-6	75.0	10,235	Runout
67-8	75.0	1,609	Failure
67-4	70.0	12,531	Runout
67-1	65.0	13,319	Runout
CONVENTIONAL SURFACE GRINDING			
67-17	50.0	420	Failure (a)
67-18	40.0	810	Failure (a)
67-23	35.0	1,646	Failure (a)
67-19	30.0	2,484	Failure (a)
67-21	30.0	2,206	Failure (b)
67-20	25.0	10,237	Runout
67-22	25.0	10,225	Runout
67-24	25.0	10,141	Runout
ABUSIVE SURFACE GRINDING			
67-9	40.0	528	Failure (a)
67-10	30.0	1,403	Failure (a)
67-15	30.0	1,767	Failure (a)
67-12	25.0	3,680	Failure
67-14	25.0	10,240	Runout
67-16	25.0	2,687	Failure (a)
67-11	20.0	10,030	Runout
67-13	20.0	10,178	Runout

(a) Multiple surface cracks

(b) Possible subsurface origin

TABLE XXIV (continued)

SUMMARY OF HIGH CYCLE FATIGUE TEST DATA FOR AF2-1DA ALLOY SOLUTION TREATED AND AGED (45 R_C)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
FINISHING EDM			
68-6	60.0	702	Failure (a)
68-1	50.0	1,790	Failure
68-2	40.0	3,249	Failure (a)
68-4	35.0	4,288	Failure (a)
68-7	35.0	4,237	Failure
68-3	30.0	10,242	Runout
68-5	30.0	10,010	Runout
68-8	30.0	9,543	Failure
ROUGHING EDM			
68-11	60.0	487	Failure
68-10	50.0	1,204	Failure (a)
68-15	40.0	2,609	Failure (a)
68-9	35.0	3,028	Failure (a)
68-12	30.0	4,875	Failure (a)
68-14	30.0	4,824	Failure
68-13	25.0	10,065	Runout
68-16	25.0	10,314	Runout

(a) Multiple surface origins

TABLE XXIV (continued)

SUMMARY OF HIGH CYCLE FATIGUE TEST DATA FOR AF2-1DA ALLOY SOLUTION TREATED AND AGED (45 R_c)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
STANDARD ECM			
69-7	90.0	490	Failure
69-2	80.0	837	Failure
69-3	70.0	2,084	Failure
69-5	70.0	2,643	Failure
69-8	70.0	2,809	Failure
69-4	65.0	10,043	Runout
69-6	65.0	10,088	Runout
69-1	60.0	10,000	Runout
OFF-STANDARD ECM			
69-14	80.0	502	Failure
69-11	70.0	950	Failure
69-9	60.0	1,963	Failure
69-12	60.0	2,324	Failure
69-16	60.0	3,558	Failure
69-10	55.0	10,008	Runout
69-13	55.0	10,110	Runout
69-15	55.0	10,115	Runout

TABLE XXV

SUMMARY OF HIGH CYCLE FATIGUE TEST DATA FOR RENE' 80 ALLOY SOLUTION TREATED AND AGED (40 R_c)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
GENTLE SURFACE GRINDING			
70-8	75.0	553	Failure (a)
70-2	60.0	1,181	Failure (a)
70-1	50.0	2,837	Failure
70-4	50.0	5,022	Failure
70-3	45.0	10,066	Runout
70-5	45.0	4,497	Failure
70-7	45.0	10,114	Runout
70-6	40.0	10,282	Runout
CONVENTIONAL SURFACE GRINDING			
70-17	40.0	251	Failure (a)
70-22	35.0	498	Failure (a)
70-18	25.0	1,636	Failure (a)
70-19	20.0	3,999	Failure
70-21	20.0	4,146	Failure (a)
70-24	20.0	10,039	Runout
70-20	15.0	12,899	Runout
70-23	15.0	10,652	Runout
ABUSIVE SURFACE GRINDING			
70-15	35.0	366	Failure (a)
70-9	30.0	568	Failure (a)
70-10	25.0	769	Failure (a)
70-11	20.0	5,349	Failure
70-13	20.0	3,087	Failure
70-16	20.0	2,418	Failure (a)
70-12	15.0	10,150	Runout
70-14	15.0	10,282	Runout

(a) Multiple surface cracks

TABLE XXV (continued)

SUMMARY OF HIGH CYCLE FATIGUE TEST DATA FOR RENE' 80 ALLOY SOLUTION TREATED AND AGED (40 R_c)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
STANDARD ECM			
74-7	60.0	308	Failure
74-1	50.0	580	Failure
74-8	45.0	1,321	Failure (a)
74-2	40.0	2,022	Failure (d)
74-3	35.0	3,825	Failure (c)
74-5	35.0	3,734	Failure (b)
74-4	30.0	10,003	Runout
74-6	30.0	10,150	Runout
OFF- STANDARD ECM			
74-9	45.0	761	Failure
74-10	40.0	1,953	Failure (c)
74-11	35.0	3,518	Failure (c)
74-15	35.0	3,819	Failure (a)
74-12	30.0	6,170	Failure (b)
74-14	30.0	10,150	Runout
74-16	30.0	10,311	Runout
74-13	25.0	10,006	Runout

(a) Possible surface shrink or IGA from ECM

(b) Surface pitting & IGA from ECM

(c) Several failure origins

(d) Secondary cracking of specimen

TABLE XXV (continued)

SUMMARY OF HIGH CYCLE FATIGUE TEST DATA FOR RENE' 80 ALLOY SOLUTION TREATED AND AGED (40 R_c)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
FINISHING EDM			
72-1	50.0	348	Failure (a)
72-2	40.0	1,194	Failure (c)
72-6	35.0	1,844	Failure (a)
72-3	30.0	9,595	Failure (c)
72-5	30.0	5,185	Failure (a)
72-8	30.0	3,496	Failure (a)
72-4	25.0	10,242	Runout
72-7	25.0	10,010	Runout
ROUGHING EDM			
72-13 q	50.0	521	Failure (a)
72-15	40.0	927	Failure (a)
72-11	35.0	1,805	Failure (a)
72-14	30.0	4,607	Failure (a)
72-9	30.0	3,345	Failure (b)
72-12	30.0	4,034	Failure (a)
72-16	25.0	10,242	Runout
72-10	25.0	10,010	Runout

(a) Surface origins

(b) Possible defect at surface; oxide discoloration or dross at edge. Origin is at surface, not in defects.

(c) Multiple surface fatigue origins

TABLE XXVI

SUMMARY OF LOW CYCLE FATIGUE TEST DATA FOR RENE' 80 ALLOY SOLUTION TREATED AND AGED (40 R_c)

Specimen No.	Pseudo Stress (ksi)	Fatigue Cycles
GENTLE SURFACE GRIND (1400°F)		
71-1	116.5	176
71-5	90	1,105
71-4	70	6,555
71-3	55	13,093
71-6	45	56,401 (a)
ABUSIVE SURFACE GRIND (1400°F)		
71-7	55	5,992
71-8	50	15,760
71-11	46	13,904

Notes:

(a) Specimen did not fail.

TABLE XXVI (continued)

SUMMARY OF LOW CYCLE FATIGUE TEST DATA FOR RENE' 80 ALLOY SOLUTION TREATED AND AGED (40 R_c)

Specimen No.	Pseudo Stress (ksi)	Fatigue Cycles
FINISHING EDM (1400°F)		
73-1	75	3,438
73-2	55	8,194
73-6	54	24,786
73-5	53	28,564
73-4	52.5	41,450
73-3	47.5	86,417 (a)
ROUGHING EDM (1400°F)		
73-8	75	3,993
73-7	55	11,764
73-11	54.5	19,335
73-10	54	24,422
73-9	52.5	57,388 (a)

Notes:

(a) Specimen did not fail.

TABLE XXVI (continued)

SUMMARY OF LOW CYCLE FATIGUE TEST DATA

FOR RENE' 80 ALLOY SOLUTION TREATED AND AGED (40 R_c)

Specimen No.	Pseudo Stress (ksi)	Fatigue Cycles
STANDARD ECM (1400°F)		
75-1	100	1,160
75-2	80	3,607
75-3	70	15,318
75-4	66	20,205
75-6	60	63,782 (a)
75-5	47.5	80,560 (a)
OFF-STANDARD ECM (1400°F)		
75-8	100	1,498
75-7	80	4,367
75-9	75	7,192
75-10	66	18,980
75-11	62	29,704

Notes:

(a) Specimen did not fail.

TABLE XXVII

SUMMARY OF FATIGUE TEST DATA FOR AISI 4340 (50 R_c)

A. GENTLE LONGITUDINAL SURFACE GRINDING WITH FATIGUE STRESS APPLIED PARALLEL TO THE GRINDING LAY

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
Surface Finish: 8 AA			
76-6	140.0	79	Failure
76-5	130.0	295	Failure
76-4	125.0	10,012	Runout
76-7	125.0	243	Failure
76-1	122.5	10,192	Runout
76-3	120.0	620	Failure
76-2	115.0	10,084	Runout
76-8	115.0	9,475	Failure
Surface Finish: 65 AA			
76-14	140.0	49	Failure
76-13	130.0	94	Failure
76-15	120.0	265	Failure
76-9	115.0	273	Failure
76-12	115.0	10,120	Runout
76-16	115.0	361	Failure
76-11	110.0	10,174	Runout
76-10	105.0	10,065	Runout
Surface Finish: 127 AA			
76-17	125.0	117	Failure
76-18	115.0	282	Failure
76-24	110.0	181	Failure
76-19	105.0	228	Failure
76-22	105.0	100	Failure
76-21	100.0	10,022	Runout
76-23	100.0	10,000	Runout
76-20	90.0	10,000	Runout

TABLE XXVII (cont.)

SUMMARY OF FATIGUE TEST DATA
FOR AISI 4340 (50 R_c)

B. ABUSIVE LONGITUDINAL SURFACE GRINDING WITH FATIGUE STRESS APPLIED PARALLEL TO THE GRINDING LAY

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
Surface Finish: 29 AA			
77-7	90.0	90	Failure
77-2	80.0	144	Failure
77-3	75.0	230	Failure
77-8	70.0	10,044	Runout
77-1	65.0	381	Failure
77-6	65.0	10,320	Runout
77-5	60.0	10,164	Runout
77-4	55.0	10,010	Runout
Surface Finish: 64 AA			
77-15	90.0	96	Failure
77-9	80.0	98	Failure
77-12	75.0	87	Failure
77-16	75.0	226	Failure
77-13	72.5	102	Failure
77-11	70.0	10,151	Runout
77-14	70.0	10,121	Runout
77-10	65.0	10,022	Runout
Surface Finish: 97 AA			
77-24	90.0	77	Failure
77-17	80.0	167	Failure
77-18	70.0	85	Failure
77-21	70.0	105	Failure
77-23	70.0	5,871	Failure
77-20	65.0	10,293	Runout
77-22	65.0	10,119	Runout
77-19	60.0	11,824	Runout

TABLE XXVII (continued)

SUMMARY OF FATIGUE TEST DATA FOR AISI 4340 (50 R_c)

C. GENTLE TRANSVERSE SURFACE GRINDING WITH FATIGUE STRESS APPLIED PERPENDICULAR TO THE GRINDING LAY

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
Surface Finish: 11 AA			
22-1	130.0	106	Failure
22-4	125.0	230	Failure
22-6	125.0	143	Failure
22-3	120.0	10,306	Runout
22-5	120.0	10,252	Runout
22-8	115.0	12,929	Runout
22-2	110.0	10,172	Runout
Surface Finish: 58 AA			
82-1	110.0	91	Failure
82-3	105.0	51	Failure
82-5	105.0	92	Failure
82-7	105.0	69	Failure
82-2	100.0	12,081	Runout
82-4	100.0	10,189	Runout
82-6	100.0	10,046	Runout
Surface Finish: 128 AA			
22-9	130.0	13	Failure
22-10	100.0	57	Failure
22-11	90.0	118	Failure
22-16	90.0	959	Failure
22-15	85.0	14,830	Runout
22-14	80.0	10,072	Runout
22-13	70.0	10,137	Runout
22-12	60.0	10,362	Runout

TABLE XXVII (continued)

SUMMARY OF FATIGUE TEST DATA
FOR INCONEL 718 (STA, 44 R_c)

A. GENTLE TURNING (FACING)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
Surface Finish: 25 AA			
79-7	90.0	319	Failure
79-6	80.0	640	Failure
79-2	70.0	933	Failure
79-1X	65.0	10,257	Runout
79-4	65.0	2,592	Failure
79-8	65.0	1,512	Failure
79-5	60.0	10,229	Runout
Surface Finish: 58 AA			
79-13	90.0	314	Failure
79-11	80.0	511	Failure
79-9	70.0	4,615	Failure
79-14	70.0	9,357	Failure
79-10	65.0	10,265	Runout
79-12	65.0	10,001	Runout
79-15	65.0	2,269	Failure
79-16	60.0	10,082	Runout
Surface Finish: 118 AA			
79-22	90.0	247	Failure
79-17	80.0	417	Failure
79-18	70.0	987	Failure
79-19	65.0	1,616	Failure
79-24	65.0	10,805	Failure
79-20	60.0	5,318	Failure
79-23	60.0	12,015	Runout
79-21	55.0	12,024	Runout

TABLE XXVII (continued)

SUMMARY OF FATIGUE TEST DATA
FOR Ti-6-6-2 (STA, 42 R_c)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
GENTLE END MILLING - END CUTTING (Surface Finish: 13 AA)			
78-1	120.0	50	Failure
78-2	100.0	217	Failure
78-3	90.0	4,371	Failure
78-4	90.0	3,818	Failure
78-5	85.0	7,371	Failure
78-7	85.0	7,282	Failure
78-6	80.0	10,069	Runout
78-8	80.0	10,487	Runout
GENTLE END MILLING - END CUTTING (Surface Finish: 55 AA)			
78-9	120.0	57	Failure
78-10	100.0	296	Failure
78-11	90.0	4,426	Failure
78-12	85.0	8,345	Failure
78-B	85.0	7,226	Failure
78-13	80.0	7,443	Failure
78-15	80.0	10,226	Runout
78-D	80.0	4,091	Failure
GENTLE END MILLING - END CUTTING (Surface Finish: 125 AA)			
78-18	120.0	31	Failure
78-19	100.0	171	Failure
78-20	90.0	4,608	Failure
78-21	85.0	2,969	Failure
78-22	85.0	9,235	Failure
78-23	80.0	6,489	Failure
78-24	80.0	8,506	Failure
78-A	80.0	6,099	Failure

TABLE XXVII (cont.)

SUMMARY OF FATIGUE TEST DATA
FOR INCONEL 718 (STA, 44 R_c)

B. ABUSIVE TURNING (FACING)

Specimen No.	Max. Stress (ksi)	Fatigue Cycles (10^{-3})	Status
Surface Finish: 76 AA			
45-14	90.0	399	Failure
45-9	80.0	650	Failure
45-10	70.0	2,013	Failure
45-11	65.0	3,015	Failure
45-13	65.0	1,713	Failure
45-16	65.0	1,704	Failure
45-12	60.0	10,000	Runout
45-15	60.0	12,449	Runout

TABLE XXVIII

STRESS CORROSION TEST RESULTS

Material	Operation	Specimen Number and Time to Fail: Gentle	Hours	Abusive	Hours
4340	End Mill	22-51	64	22-56	45
		22-52	142.5	22-58	142.5
		22-53	64	22-59	64
		22-54	111.5	22-60	88
4340 Mod.	Surface Grind	23-28	95.5	23-32	28.5
		23-29	95.5	23-33	28.5
		23-30	95.5	23-34	30.5
		23-31	50.0	23-35	15.5
	Hand Grind	24-19	30.5	24-23	87.5
		24-20	95.5	24-24	29.0
		24-21	30.5	24-25	47.5
		24-22	39.5	24-26	39.5
	End Mill	25-19	64.0	25-23	47.5
		25-20	64.0	25-24	72.0
		25-21	64.0	25-25	27.0
		25-22	39.5	25-26	19.5
Grade 300 Maraging Steel	Surface Grind	28-28	654	28-32	1000NF
		28-29	1000NF *	28-33	1000NF
		28-30	1000NF	28-34	1000NF
		28-31	453.5	28-E	207
	Hand Grind	29-19	236	29-23	286.5
		29-20	1000NF **	29-24	359
		29-21	***	29-25	845.5
		29-22	283	29-26	215
	End Mill	30-19	1000NF	30-23	1000NF
		30-20	1000NF	30-24	1000NF
		30-21	1000NF	30-25	1000NF
		30-22	1000NF	30-E	495.5

* No failure when test terminated - very small cracks evident.

** End cracked at fixture sometime less than 1000 hours but not detected.

*** Specimen incorrectly fabricated.

APPENDIX I

DETAILED MANUFACTURE OF TEST SPECIMENS

I-1 General Preparation of Specimens

I-2 Test Cuts - Surface Grinding

I-3 Test Cuts - Hand Sanding

I-4 Test Cuts - Milling

I-5 Test Cuts - Turning

I-6 Test Cuts - Drilling

I-7 Test Cuts - Electrical Discharge Machining (EDM)

I-8 Test Cuts - Electrochemical Machining (ECM)

APPENDIX I-1

General Preparation of Specimens

The general procedure used was to saw blanks, perform any necessary heat treatment and then reduce blanks to a size suitable for producing the various test cuts or test surfaces which were to be studied. After these test cuts were made, the specimens were finish manufactured, making them ready for testing. The following table summarizes the amount of metal which was removed in taking the test cuts on the various types of specimens and using the various metal removal processes.

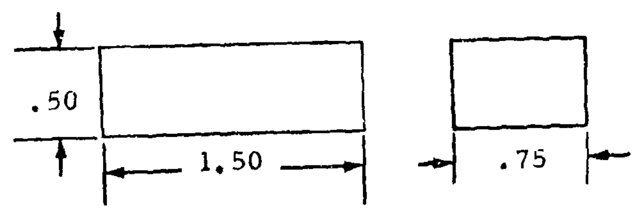
Depth of Test Cut (inches)

Machining Process	Metallography	Residual Stress	Fatigue	Stress Corrosion
Surface Grinding	.010	.010	.010	.010
Hand Grinding	.002	.002	.002	.002
End Mill-End Cut	.030	.030	.030	.030
End Mill-Peripheral Cut	.030	.030	.030	-
Turning	.010	.010	.010	--
EDM	.045	.070	.045	--
ECM	.045	.070	.045	--

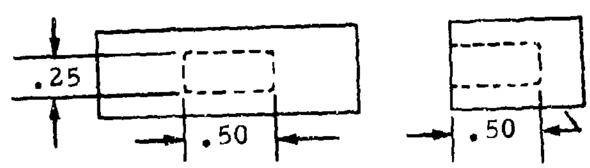
Specimens for residual stress, stress corrosion, and fatigue tests were prepared in accordance with Figures 6 through 11 of the main report (Section 5.3). Whenever residual stress or fatigue specimens were made using a particular set of metal removal variables, the coupons required for metallographic studies were cut from these specimens. In several instances, however, combinations of cutting parameters were subjected to metallographic evaluation only. In those instances, metallographic coupons as shown in Figure A were specifically prepared for that purpose.

Metallographic Samples

Most metallographic samples were taken from fatigue specimens in one of two conditions:



Blank Prior to ECM Test Cut



Finished ECM Coupon

Figure A
METALLOGRAPHIC COUPON USED FOR ECM

1. Samples were removed from the fatigue coupon after the test cut was made but before the gage section was contoured. The sectioning was done in such a way that the area removed from the coupon would not affect the finished specimen geometry.

2. Metallographic samples were also taken from fatigue specimens after testing was completed.

Metallographic coupons were also obtained from the ends of residual stress specimens prior to testing. In all cases, sectioning of the metallographic samples from the various sources was accomplished using a silicon carbide slitting wheel.

Residual Stress Specimens

Residual stress specimens were made in conformance with Figure 6. After the blanks were heat treated, these specimens were rough milled and then further reduced by low stress grinding to obtain the final thickness of specimen required prior to making the test cut. Details of these milling and grinding procedures are noted in Table I. The test cut was then made on one side of the specimen as detailed in Appendix I-2 to I-8. On the completion of the test cut, the residual stress specimens were considered to be ready for evaluation.

Additional grinding stock (.010 in.) was left on the backs of the ECM and EDM specimens to compensate for excessive warpage of the specimen during the test cuts, should it occur. Low stress grinding per Table I was used on the back surface of these specimens after the test cut was completed in order to reduce the specimen to the final dimensions shown in Figure 6.

High Cycle Fatigue Specimens

High cycle fatigue specimens as described by Figures 7 and 8 were milled and low stress ground as indicated in Table I to the point of being ready for the test cut. Test cuts were taken on both sides of the fatigue test specimen before the coupon was contoured to obtain the constant stress gage section. See Appendix I-2 to I-8 for details. After the test cuts were completed, the gage section was contoured by low-stress plunge grinding. The edges of the test section were polished longitudinally and given a 1/32 in. radius by hand finishing. The edges of the gage section were then shot peened as detailed in Figure 7. At this point, the fatigue specimens were ready for test.

Low Cycle Fatigue Specimens

Low cycle fatigue specimens were made in accordance with Figures 9 and 10. Figure 9 describes the specimen used to evaluate conventionally machined

surfaces such as milling, grinding, and facing. The specimen shown in Figure 10 was used to evaluate test surfaces finished by EDM and ECM. In manufacturing specimens, the heat treated blanks were milled and then low stress ground as indicated in Table I to the point of being ready for the test cut. Test cuts were then made on both sides of the fatigue test specimens. In the case of the conventional machining operations, the entire surfaces were machined. In the case of EDM and ECM test surfaces, a pocket which would encompass the gage section was cut on each side of the specimen. The overall surface machining versus the electrically-assisted pocket accounts for the difference in specimen design, Figure 9 versus Figure 10.

After the test cuts were completed, the gage section was contoured by low stress plunge grinding. The edges of the test sections were then polished longitudinally and given a 1/32 in. radius by hand finishing. The edges of the gage section were then shot peened as shown in the specimen drawing. The purpose of the peening is to prevent failures at the edges where a stress concentration occurs. Forcing the failure to occur away from the edge or corner is intended to provide fatigue data representative of the plane machined surface. After peening, the specimens were ready for low cycle fatigue testing.

Stress Corrosion Specimens

Stress corrosion specimens were made in accordance with Figure 11. After the blanks were heat treated, these specimens were rough milled and then further reduced by low stress grinding to obtain the final thickness required prior to making the test cut. Details of these milling and grinding procedures are noted in Table I. The test cut was made on one side of the specimen as detailed in Appendix I-2, I-3 and I-4. On completion of the test cut, the stress corrosion specimens were considered to be ready for evaluation.

Test Cuts

At the appropriate point in specimen manufacture, test cuts were made on the gage section of specimens using the variety of metal removal methods and variables being studied by this effort. A summary of the specific cutting conditions used to manufacture test specimens is as follows:

Material Removal Method	Table No.
Surface Sanding	II
Hand Grinding	III
End Milling-End Cutting	IV
End Milling-Peripheral Cutting	V

Material Removal Method	Table No.
Turning	VI
Drilling	VII
Electrical Discharge Machining (EDM)	VIII
Electrochemical Machining (ECM)	IX
Surface Finish Study	X
Post Treatments	XI

Surface Finish

Surface finish measurements were made on each specimen after manufacturing. A stylus type instrument, a Model BL-185 Surfindicator, was used. All surface finish readings contained in this report are average values taken perpendicular to the lay of the surface (when present). A cutoff of .030" was used for surfaces of 30 microinches or greater. A cutoff of .010" was used for surfaces less than 30 microinches.

APPENDIX I-2

Test Cuts - Surface Grinding

The grinding test cuts were performed at Metcut using a Norton 8 in. by 24 in. hydraulic surface grinder driven by a 2 HP variable speed drive. The variables used in grinding the material involved in this contract will be described in the Tables of Test Conditions, Table II.

The high strength steel specimens were held in place during grinding by a magnetic chuck. The titanium and nickel base alloys were mechanically clamped to a table of the grinder. Specimens were positioned on the table so that the grinding marks or "lay" of the ground surface was as shown in Figure 12.

In the basic portion of this program, specimens were produced by either gentle, conventional or abusive conditions. A single set of grinding parameters was used to produce each of the three conditions. However, in the surface finish study, three different sets of grinding parameters were used to produce the gentle conditions and three others to produce abusive conditions. Each set of parameters produced a different level of surface roughness.

In making these specimens, all conditions in the surface other than roughness were held as constant as possible. Normally, surface grinding of hardened 4340 would produce a finish between 30 and 50 microinches (AA). Experimentally, however, grinding conditions were developed which produced surface finishes ranging from 8 to 125 AA. This was done in both gentle or low stress grinding and in abusive grinding.

It was found that the wheel dressing procedure was the single most important variable in obtaining the desired range of surface finish. The best finishes were produced using a low speed of diamond dressing across the wheel and light diamond infeed. This procedure resulted in a finely dressed grinding wheel. On the other hand, the rougher surface finishes were produced by a faster dressing traverse and higher infeed of the dressing tool. These procedures resulted in an open grinding wheel. The specific conditions developed to produce both low stress and abusive grinding over the range of 8 to 125 AA are summarized in Table X.

APPENDIX I-3

Test Cuts - Hand Sanding

Disc sanding was chosen to provide grinding or sanding conditions representative of actual production hand finishing operations. An aluminum oxide, resin bond on cloth was used as the abrasive material to produce the test surface. The surface "lay" produced by this operation was oriented in the same manner as the transverse turning and end milling shown in Figure 12.

It is interesting to note that the manual disc sanding time for the titanium alloy samples was approximately three times greater than those for the steel samples for removal.

After hand grinding the initial specimen, excessive thinning near the corners existed. A picture-type frame made from steel strips was used to support the edge on the following specimens. This type of fixture was necessary in order to maintain uniform edge thickness. The conditions used for hand sanding in this program are given in Table III.

APPENDIX I-4

Test Cuts - Milling

End milling tests were performed on a Cincinnati No. 3 horizontal high speed, dial type milling machine. In performing the test cuts, specimen coupons were bolted down to a suitable baseplate in order to hold them flat. The bolt holes in the blanks were located so as to be removed during subsequent specimen manufacture. A photograph of a milling setup, along with the coupon holding fixture is shown in Figure B.

End Cutting

The end milling cutter was a 4 in. diameter, five-tooth inserted blade cutter with an integral tapered shank. This particular c tter, fitted with brazed carbide inserts, is shown in Figure C.

Peripheral Cutting

The peripheral milling cutter was manufactured by Boeing/Seattle and was loaned to Metcut for this particular project. The teeth of this cutter were twisted carbide inserts, mechanically clamped to the cutter body, as illustrated in Figure C.

Milling conditions used for test cuts of specimens covered in this particular report are summarized in Tables IV and V.

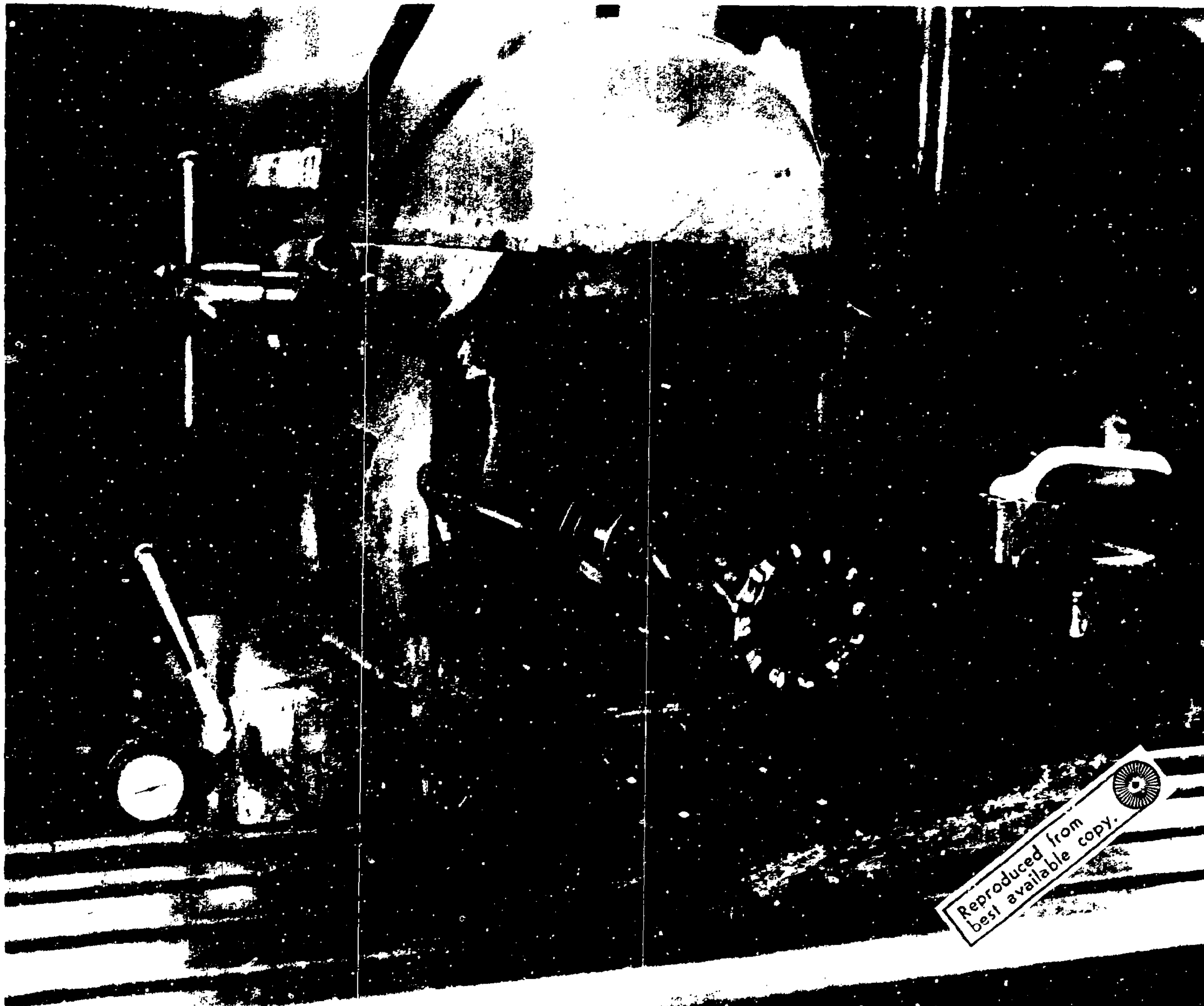


Figure 3
SETUP USED FOR END MILLING TEST CUTS

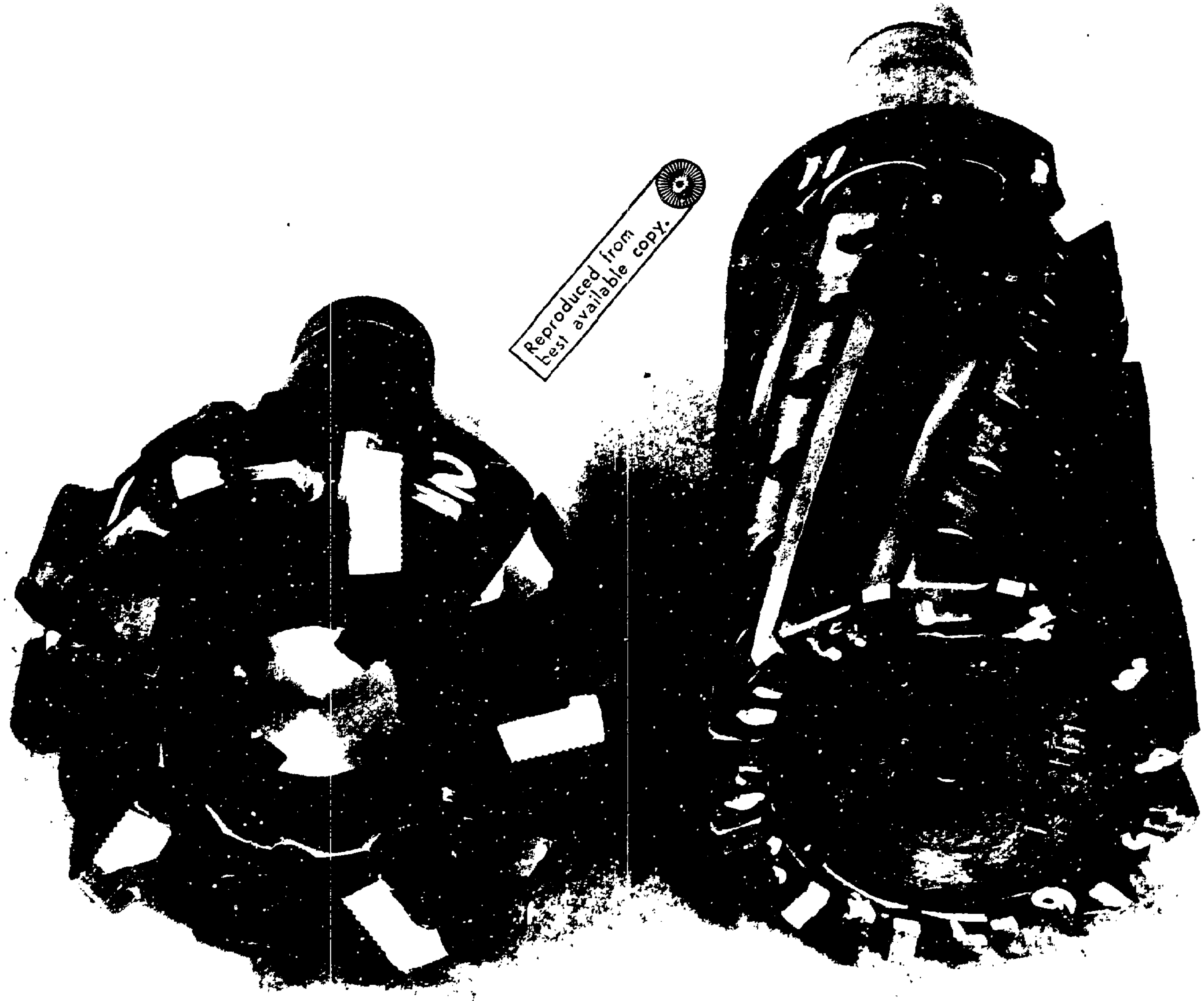


Figure C
END AND PERIPHERAL MILLING CUTTERS

APPENDIX I-5

Test Cuts - Turning

The turning tests (facing) were performed on a 16 in. by 54 in. LeBlond heavy duty lathe equipped with a 30 HP variable speed drive. The setup is shown in Figure D. As shown in this figure, the specimen blanks were bolted down to a faceplate for making the test cuts. The bolt holes in the blanks were located so as to be removed during subsequent specimen manufacture. The complete list of cutting conditions for turning is given in Table VI. In gentle turning, the various surface finishes were produced by changing the nost radius of the tool and the feed, other conditions remaining constant. The principal difference between gentle and abusive turning was the sharpness of the tool, as measured by the wearland. The wearland was .030 in. for abusive turning and 0 - .004 in. for gentle turning.

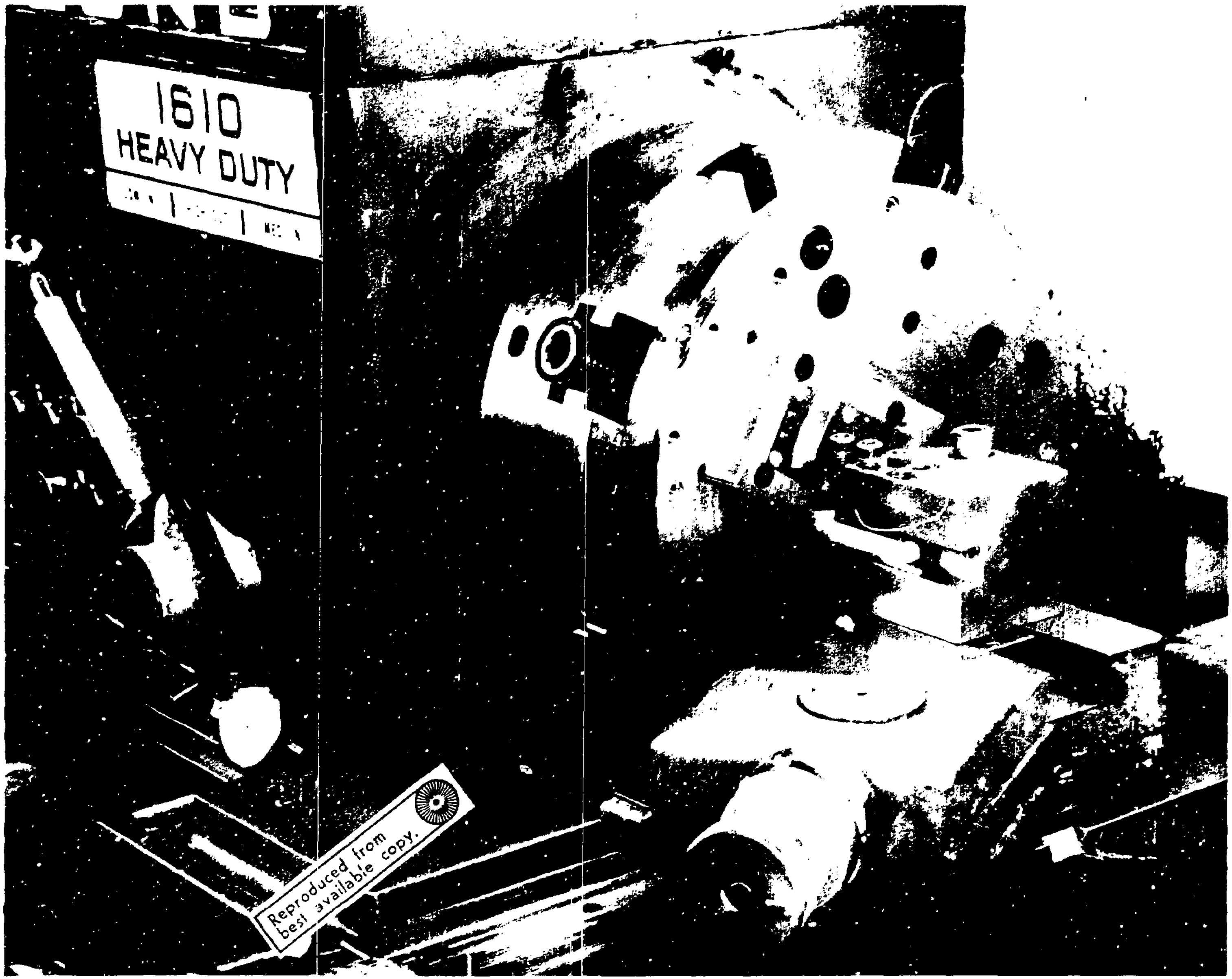


Figure D
SETUP USED FOR TURNING (FACING) TEST CUTS

APPENDIX I-6

Test Cuts - Drilling

Test cuts were made in small coupons on a Cincinnati 16 in. Sliding Head Box Column Drill. The coupons were fixed in a small table vise. Positive feed was used on all drilling operations. A summary of the gentle and abusive drilling conditions used on all three of the test materials is presented in Table VII.

APPENDIX I-7

Test Cuts - Electrical Discharge Machining (EDM)

The electrical discharge test cuts were accomplished by General Electric/ Evendale using an Elox HRP 104 EDM machine with an NPS D100 power supply. In the previous AFML surface integrity contract with Metcut, this same basic machine was used. At that time, however, a rotating-traversing brass electrode was used to produce the specimen blanks. This fixturing has been modified for the present contract in that a reciprocating plunge type of motion has been developed. An overall view of the Elox equipment with the appropriate fixturing in place is shown in Figure E. A closeup view showing the copper electrode and a specimen blank clamped in place is shown in Figure F. In operation, dielectric fluid is flushed through two ports in the electrode. The dielectric fluid, Texaco 499 EDM oil, flushes over the specimen from two slots in the electrode which are perpendicular to the direction of stroke. The equipment is set up operate on a 3 in. maximum stroke at a frequency of 45 strokes per minute.

A photograph of a specimen blank before and after the EDM operation is shown in Figure G. A complete table of the EDM parameters used on this program are given in Table VIII.

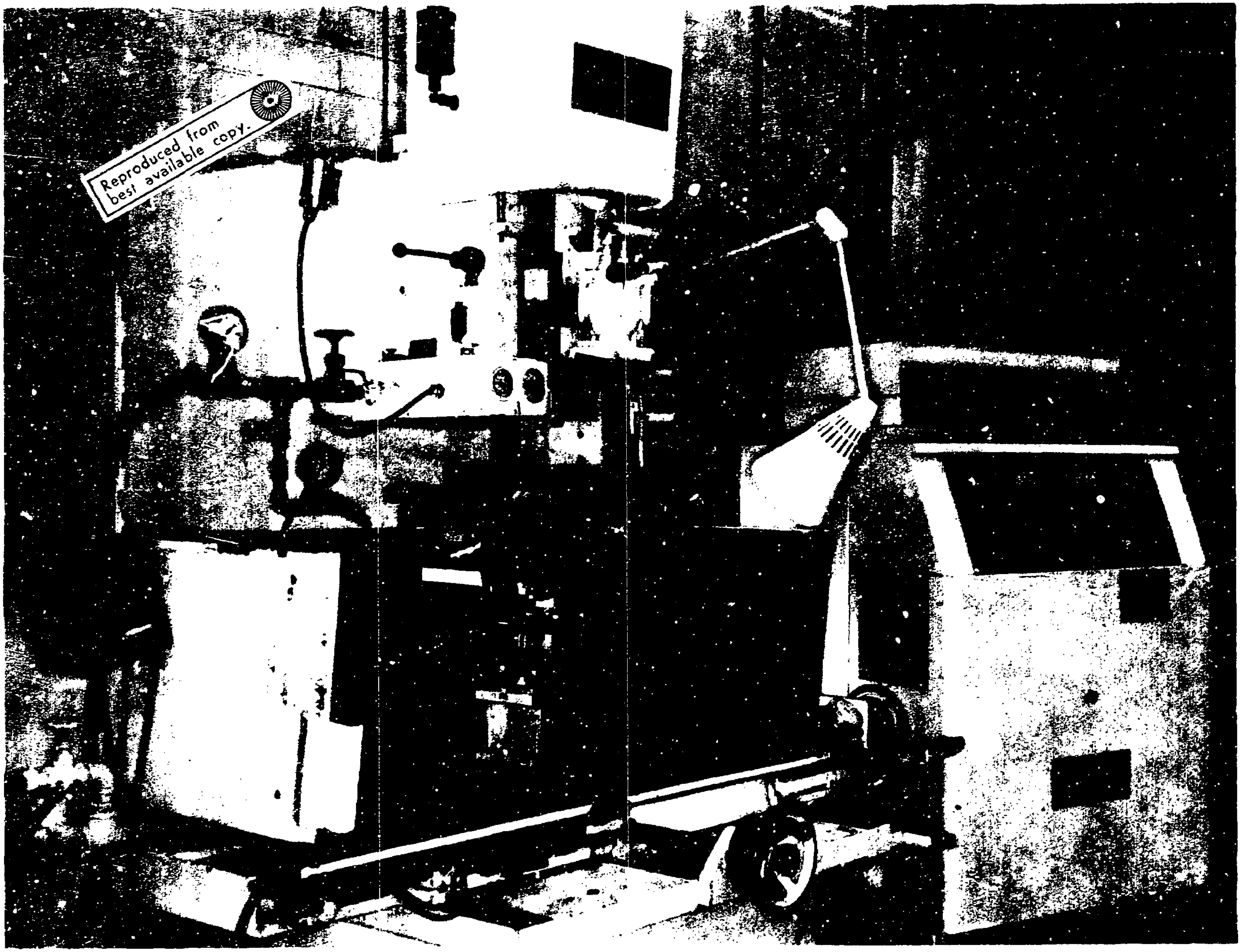


Figure E
EQUIPMENT USED FOR EDM TEST CUTS

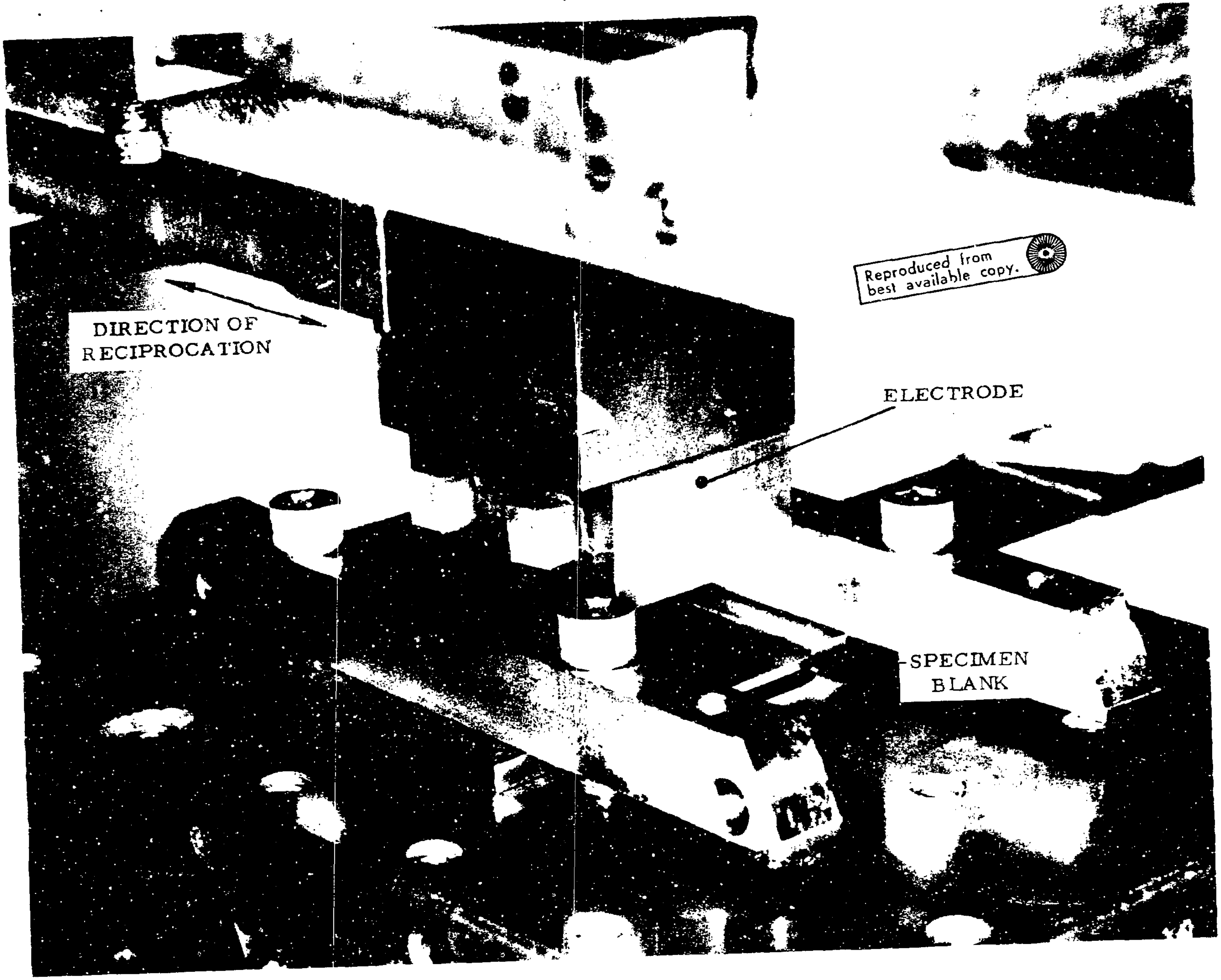


Figure F
CLOSEUP OF EDM SETUP SHOWING FINISHED SPECIMEN BLANK

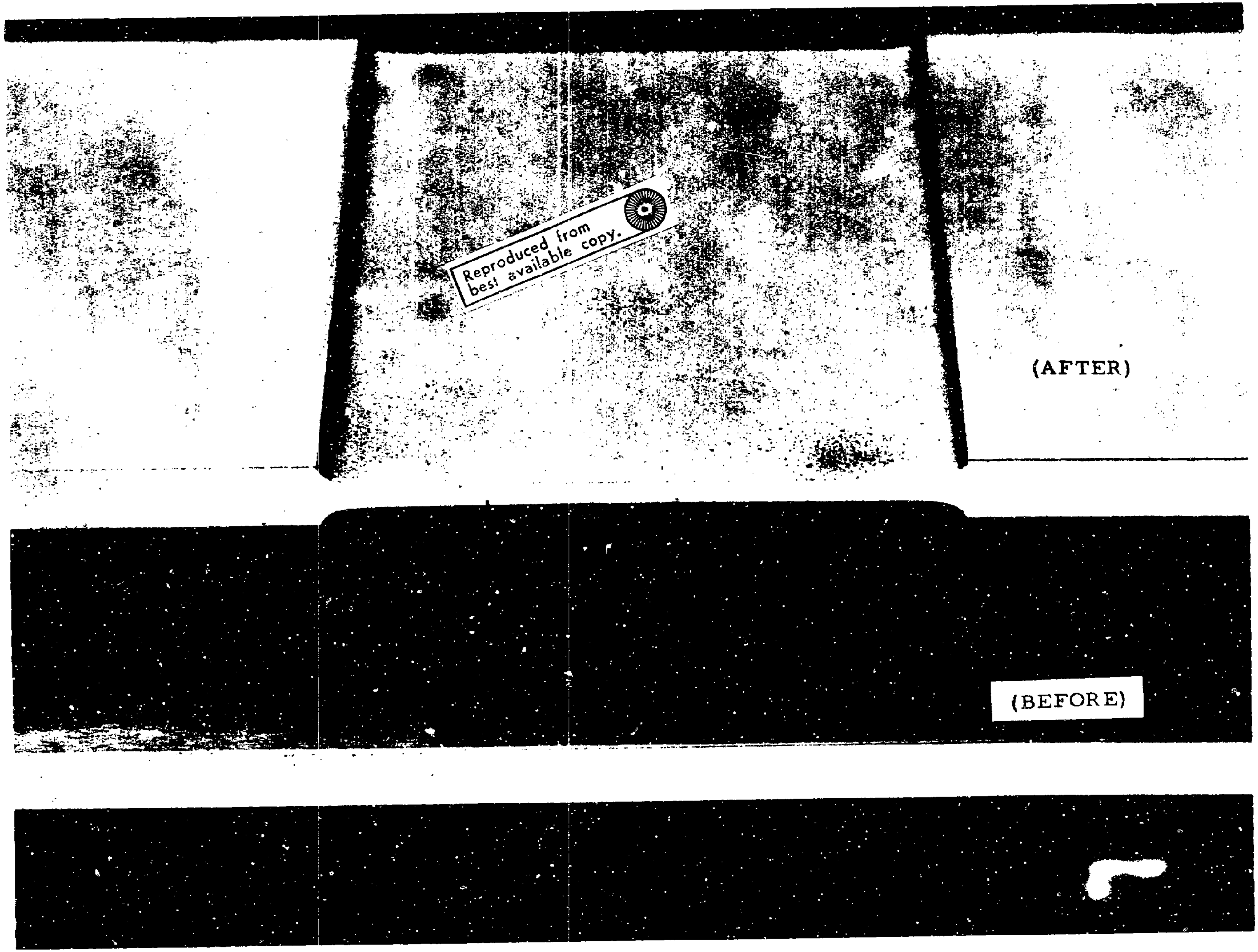


Figure G
FATIGUE COUPON BEFORE AND AFTER EDM TEST CUT

APPENDIX I-8

Test Cuts - Electrochemical Machining (ECM)

The electrochemical machining of fatigue specimens was accomplished by General Electric/Evendale using a Cincinnati Milling Maching Company Triplex ECM machine. The power supply used was a Rapid Electric 30 volt, 10,000 amp rectifier. The electrolyte studies were made on a small laboratory unit constructed by G. E., equipped with a Metal and Thermite 25 volt, 1,500 amp power supply.

The ECM tooling used to produce ECM test cuts on specimens is shown in Figures H and J. The particular set of tooling shown in these illustrations is for the production of low cycle fatigue test specimens. That used for the other specimen configurations is similar. Figure H shows the fully assembled fixture, while Figure J shows the components disassembled but with a specimen blank in place. The flow of electrolyte is down one side of the electrode, across the ECM gap, and out the opposite side of the tooling. Electrolyte used for the Rene' 80, Inconel 718, and Ti-6Al-6V-2Sn specimens was 1 lb./gallon NaCl. For AF2-1DA and AF 95, the electrolyte was 2 lb./gallon $NaNO_3$.

Dimensions of the cutting face of the electrodes were as follows:

> High cycle fatigue specimen electrode rectangular, 1.5 in. by 1.75 in.
>
> Low cycle fatigue specimen electrode rectangular, 1.75 in. by 3.5 in.
>
> Residual stress specimen electrode rectangular, 1.0 in. by 5.0 in.

The complete list of conditions used in ECM machining on this program is given in Table IX.

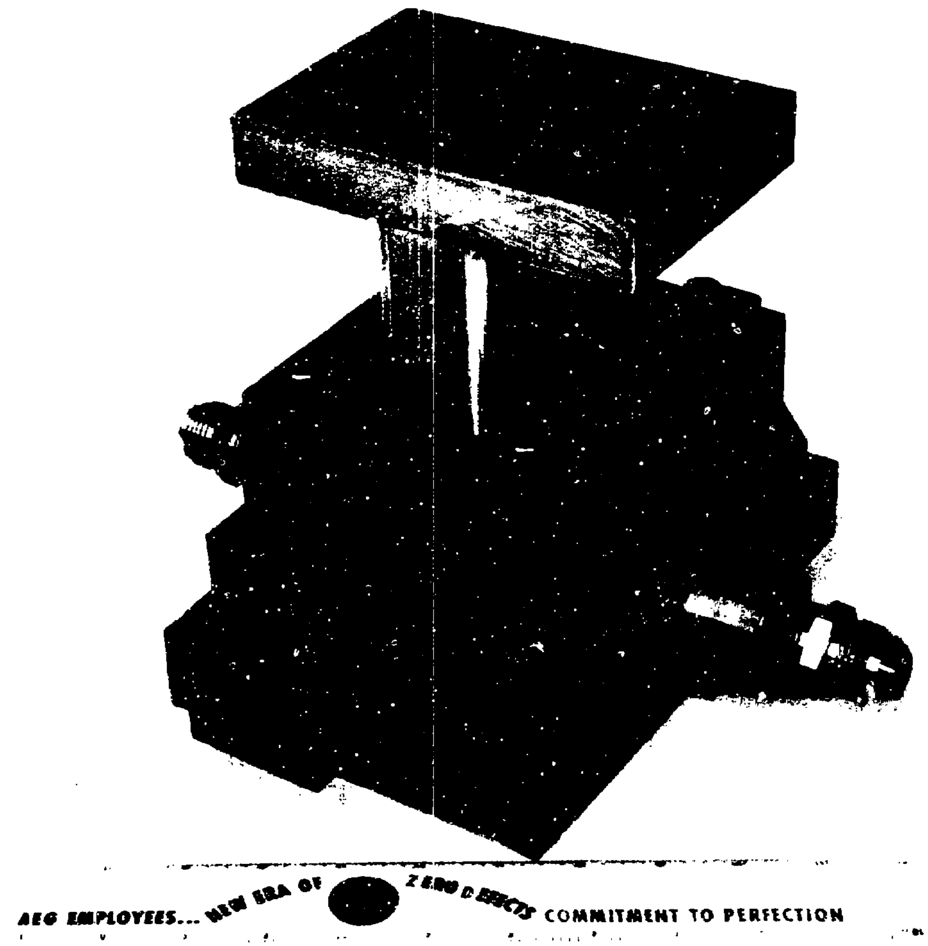


Figure H
ECM TOOLING FOR LOW CYCLE FATIGUE SPECIMENS

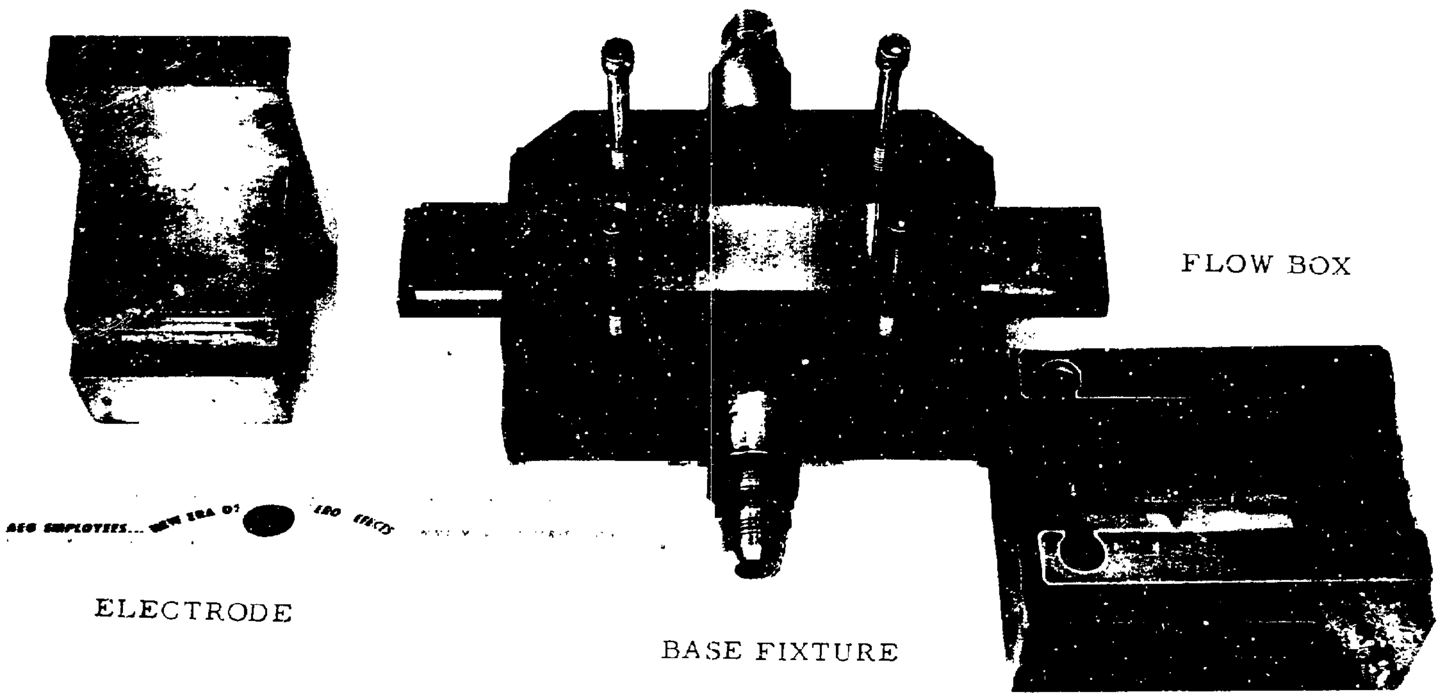


Figure J
COMPONENTS OF ECM TOOLING

APPENDIX II

DETAILED PROCEDURES

APPENDIX II-1

Metallurgical Procedures

Specimens used for metallographic studies were obtained from portions of fatigue or residual stress coupons or from specifically prepared metallographic coupons. All samples were sectioned by standard metallographic techniques using a silicon carbide cutoff disk flooded with a water-base coolant to prevent overheating. Samples were then ground back using an abrasive belt plus coolant. At this point, they were mounted using a special procedure which was developed in order to provide maximum edge retention during the metallographic polishing operation. An outline of this procedure is as follows:

- Cast samples in a 1-1/4 in. diameter mold with a mixture of an epoxy resin and a suitable hardener plus a fine grit pellitized aluminum oxide filler.

- Place mounts in a vacuum changer during the initial setting period. (This step facilitates air removal, minimizes the possibility of voids between the met l sample and the mounting plastic, and also improves the adherence of the mounting compound to the surface of the sample.)

- Cure mounts at a temperature not exceeding 70°F for approximately 12 hours.

- Grind and polish specimens metallographically using an automatic mechanically driven polishing unit of the positive positioning type. Successively finer silicon carbide papers, to 600 grit, followed by diamond paste on suitable cloths are used to achieve the final metallographic polish.

After polishing, samples were etched using reagents suitable for the alloy involved. Etchants used for the current test materials were as follows:

Titanium Alloys: HF, HNO_3, H_2O
Steel Alloys: Nital, 2%
Nickel Base Alloys: Kalling's

In order to characterize surface hardness gradients, Knoop microhardness readings were taken using a Tukon machine. One hundred gram and five hundred gram load ranges were generally used at depths greater than .005 in. from the surface of the specimen. In order to obtain valid readings,

and to minimize the possibility of edge yielding under these loads, series of 10 and 25 gram Knoop readings were taken on most specimens in the first .002 to .005 in. from the surface.

Direct Rockwell readings were also taken on all samples to determine the base hardness.

All data presented in this report have been normalized and converted from Knoop values to Rockwell values using standard calibration and conversion procedures.

APPENDIX II-2

Procedures for Measurement of Residual Stress

A surface layer removal technique was used to determine the residual stress data presented in this report. The procedure using the specimen shown in Figure 6 of this report consists of successively etching off thin layers of the stressed surface of the specimen and determining the corresponding change in specimen curvature. The actual curvature measurement is made by measuring change in deflection over a fixed span of 3.5 in. The fixture used for making these measurements is shown in Figures K and L.

Successive layer removal was accomplished on titanium and steel alloys by etching, which consisted of total immersion of the samples for short intervals of time in an acid bath. The backs of the sample were "stopped-off" with a lacquer so that the etching action would be confined to the test surface only. Twenty percent HF was used on the titanium specimens; 10 to 15 percent HNO_3 was used on the steel specimens.

In working with the nickel base alloy specimens, an electrolytic swabbing method was used to remove controlled amounts from the test surface. The electrolyte consisted of 25 percent HCl. The setup for this electrolytic etching technique is shown in Figure M.

After each etching step, the thickness of the specimen was measured at 10 to 12 different stations to the closest .0001 in. with an indicating micrometer. Localized etching would be accomplished as necessary to achieve uniform layer removal. The thickness of stock removed versus the change in deflection data is then used to calculate the residual stresses at each measured step below the surface of the specimen. The uniaxial stress in the longitudinal direction of the test specimen was calculated using an equation developed by F. Stablein. *

$$S_n = \frac{E}{3L^2}\left[(H-h_n)^2 \left(\frac{df}{dh}\right)_n - 4(H-h_n)(f_n) - 2(h_n f_o) - 2\int_o^h f dh \right]$$

* Stablein, F. - "Spannungsmessungen an einsertig abgeloschten Knuppeln" - Kruppsche Monatshefte, Vol. 12 (1931) pp. 93-98.

Where: S_n = Residual stress, pounds/square inch

H = Initial thickness of the test specimen, inches

h = Stock removed to any depth, inches

f = Deflection of specimen at any depth, inches

f_o = Initial deflection of the test bar, inches

L = One-half gage length, inches

E = Modulus of elasticity, pounds/square inch

$\frac{df}{dh}$ = Slope at any point on deflection versus stock removed curve

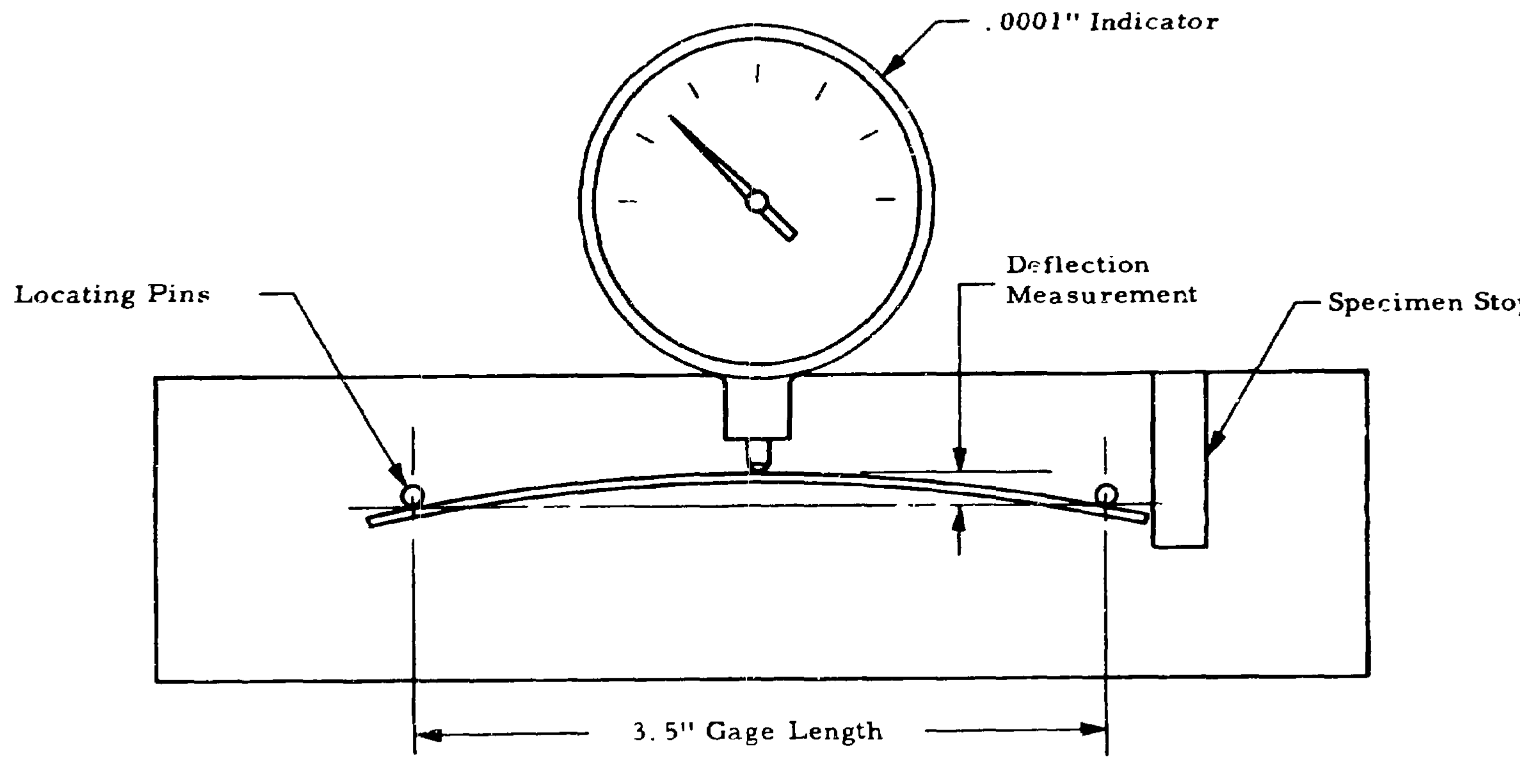


Figure K
DEFLECTION MEASUREMENT FIXTURE

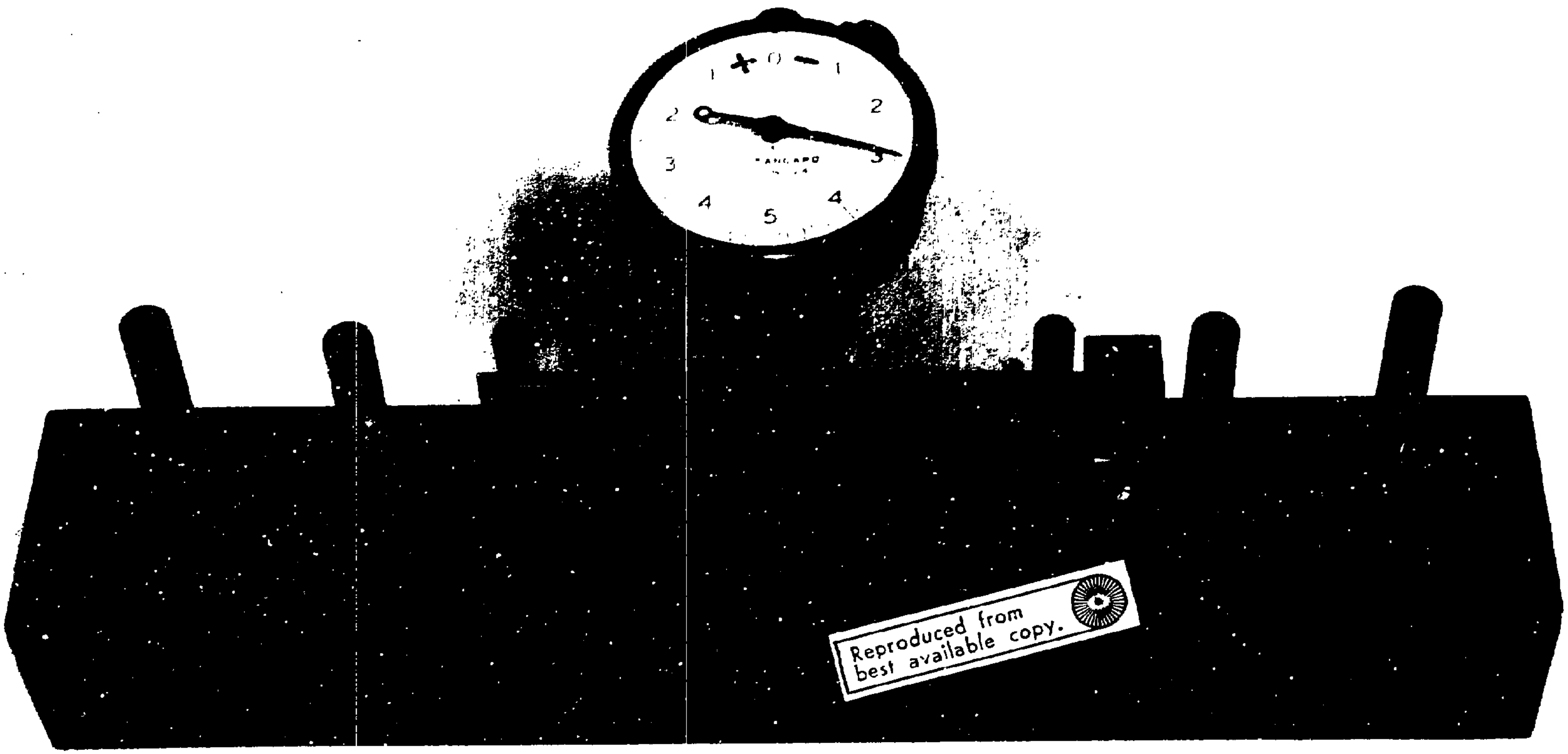


Figure L

FIXTURE FOR MEASURING DEFLECTION OF RESIDUAL STRESS TEST SPECIMEN.

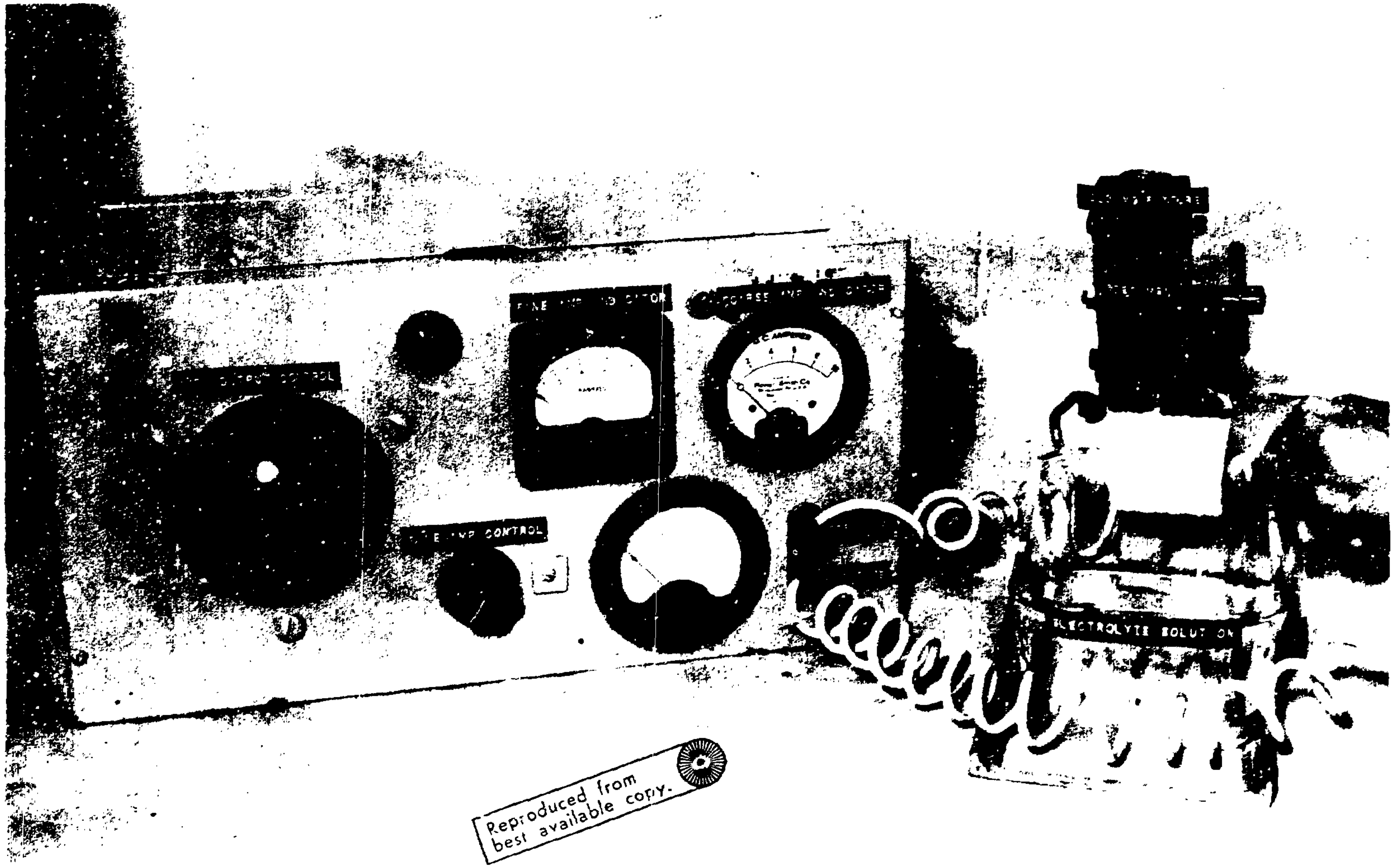


Figure M

ELECTROLYTIC APPARATUS USED FOR DIFFERENTIAL ETCHING OF RESIDUAL STRESS SPECIMENS

APPENDIX II-3

High Cycle Fatigue Testing Procedures

All fatigue tests summarized in this report were run on cantilever bending specimens at room temperature under fully reversed loading. All tests on titanium were run at Metcut using Sonntag SF-2-U or SF-01 fatigue machines. These units are mechanically excited, constant force machines, and operate at a constant speed of 1800 cpm. Load verification was obtained by standard calibration procedures involving the dynamic readout of instrumented specimens using a light beam oscillograph and cross calibration with specimen deflection measured optically.

All tests on AF 95 were run by General Electric/Evendale. G. E. used a modified Krouse type cantilever bending fatigue machine. The modification consisted of a change in the mechanical coupling to convert this unit from a constant displacement to a constant force machine. In setting up each individual test, the specimen was loaded statically with a load calculated to produce the desired stress in the test section of the specimen. The corresponding static deflection was noted. When the test machine was started dynamically, the dynamic deflection was adjusted so that the half amplitude was equal to the static measurement. Specimen life is monitored with an automatic cycle counter.

High cycle fatigue tests were run by General Electric/Evendale using the procedure described above.

In reporting test results, runout stresses are the initially calculated stress of the maximum stress in the test section of the specimen. Failure stresses are back calculated and indicate the actual stress at the origin of failure, which may be less than the maximum stress in the specimen.

Thermocouples, used to monitor and to control temperature, were tack-welded to the larger specimen tab adjacent to the gage section. The grips were wire resistance heated to 450°F and the specimen temperature was allowed to stabilize. An induction coil powered by a model T-2.5-1KC-TBW, type T-254-72 Lepel induction heater was used to heat the specimen gage section to 1000°F. Temperature control was achieved using one of the thermocouples tack-welded to the specimen tab. The gage section temperature was monitored using a model 300T3 Ircon infrared pyrometer. The material's emissivity was obtained using a specimen instrumented with tack-welded thermocouples; the gage section temperature at all points was within 10 degrees of the desired test temperature. Temperature stabilization was allowed for one hour. After the soak period, a calibration curve was obtained at temperature and the test was started as described above for the room temperature tests.

APPENDIX II-4

Low Cycle Fatigue Testing Procedures

Low cycle fatigue testing was performed in fully reversed bending at 15 cycles/minute. The equipment in use at Metcut is a hydraulically driven servo-controlled unit. An overall view of this apparatus is shown in Figure N. A closeup of a test specimen mounted in the bending fixture is shown in Figure P.

The test equipment was calibrated by relating the controlled parameter, fixture amplitude to surface strain in the gage section. This relationship was established by plotting surface strain measured with strain gages as a function of fixture amplitude. Agreement within 1 to 2 percent was obtained between strain calculated from specimen curvature as measured with a spherometer and strain measured with resistance strain gages. These two methods of strain determination are valid beyond the elastic limit of the material. For stresses below the elastic limit, strain calculated from the applied load and fixture geometry agreed with values obtained from spherometric and strain gage measurements.

Low cycle fatigue tests were run and tabulated in terms of pseudo stress. This value is a product of the specimen strain times the elastic modulus of each alloy. The stress value is artifically high since specimen surface yielding frequently occurs under low cycle fatigue (LCF) stress conditions. The actual stress as determined by loads supplied does not actually reach the high level as indicated by the pseudo stress value. This procedure, however, is a conventional way of handling LCF data. Perhaps more often, LCF data is reported in terms of strain rather than stress. This complexity appears unnecessary in this report, however, Among other things, it complicates the relationship between low cycle and standard high cycle fatigue data.

After loading, tests are run under constant strain conditions as determined by maintaining a constant peak curvature of the test specimen. A spherometer, which is an electrical readout device consisting of three probes which contact the ends and the midpoint of the gage section, is used to determine curvature. This value can be read intermittently or monitored continuously as desired. Control of the low cycle fatigue device itself is achieved through maintaining a constant cyclic fixture amplitude which is adjusted as nec- sary to maintain constant peak curvature of the specimen, hence constant strain.

Low Cycle Fatigue Testing Procedures (continued)

Elevated temperature tests were performed by radiantly heating the center 1 in. portion of the gage section. The spherometer was used to verify the strain level in the presence of the thermal gradient. No difference was detected in the strain obtained at room and elevated temperatures for a given fixture amplitude. The temperature in the one inch hot portion of the gage section was maintained within $\pm$ 10° F of the test temperature.

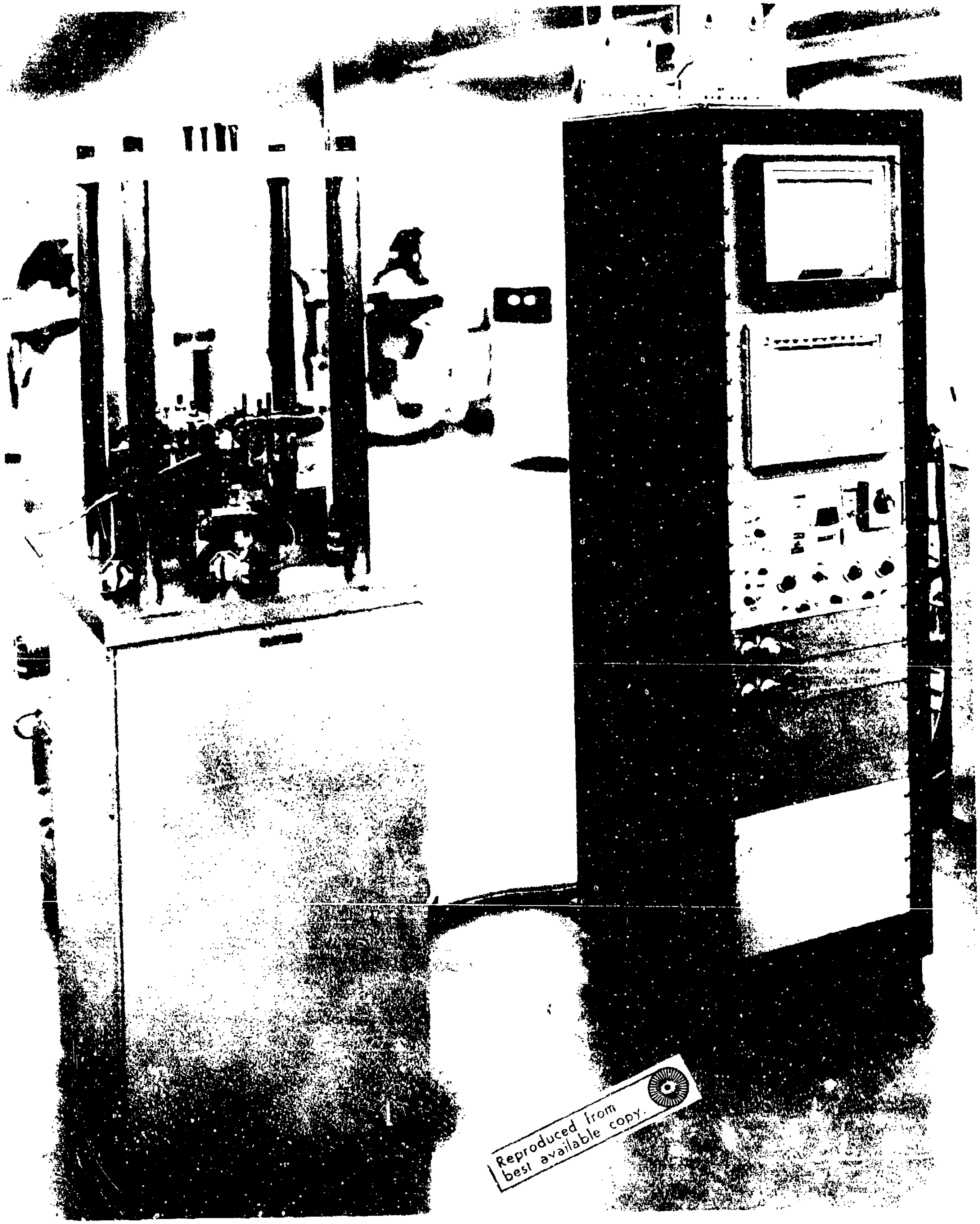


Figure N LOW CYCLE FATIGUE TESTING APPARATUS

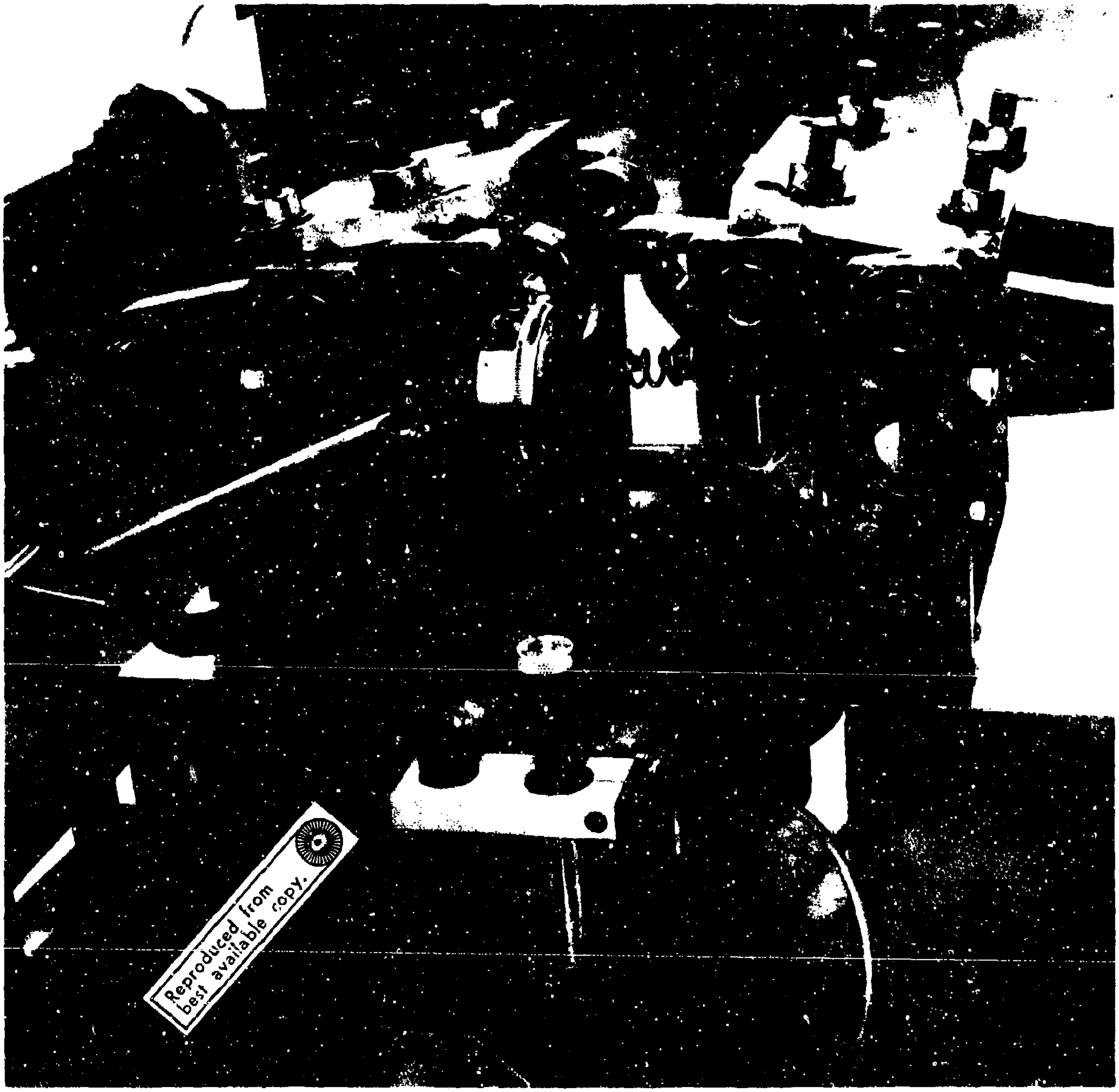


Figure P

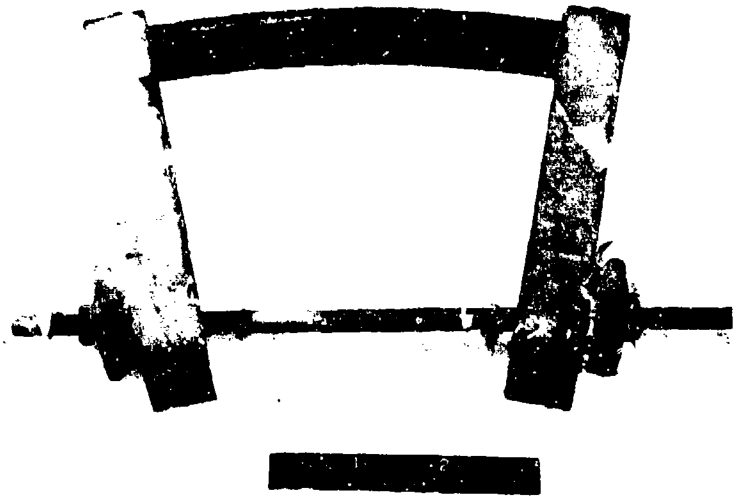
CLOSEUP OF LOW CYCLE FATIGUE TEST FIXTURING

APPENDIX II-5

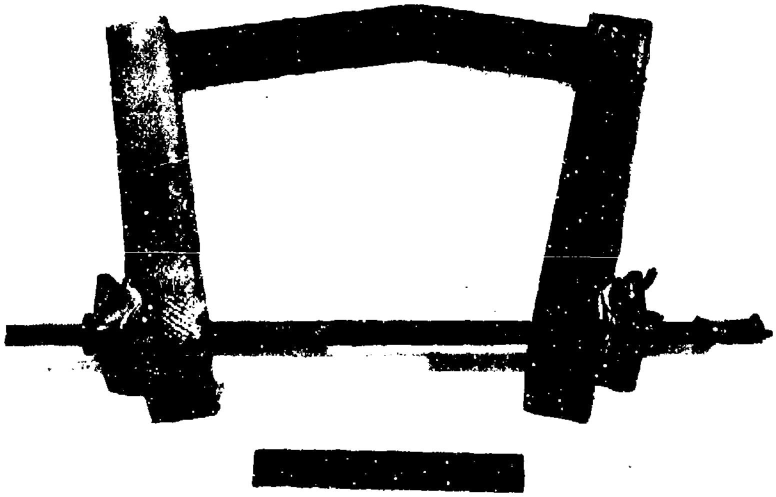
Procedure for Stress Corrosion Evaluation

Specimens per Figure 11 were clamped into fixtures which prestrained them in bending as shown in Figure Q. Specimens were stressed to approximately 75% of the yield strength of the material. They were exposed until failure or an elapsed time of 1000 hours, whichever occurred first. The exposure environment consisted of 3.5% sodium chloride solution at room temperature meeting the purity of pH requirements of Method 811 of Federal Test Method Standard 151. Alternate immersion between the salt solution and air was accomplished on a continuous exposure cycle of 10 minutes immersion in the solution and 50 minutes out of the solution. Samples were examined approximately once each day and failure times noted. A photograph of a typical failed specimen is also included in Figure Q.

All stress corrosion testing was accomplished at Boeing/Seattle.



BEFORE FAILURE



AFTER FAILURE

Figure Q
PHOTOGRAPHS OF 4340 TEST SPECIMENS MOUNTED
IN STRESS CORROSION FIXTURING

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13. ABSTRACT

A surface integrity evaluation of several iron, titanium and nickel base structural alloys has been completed. Materials investigated include AISI 4340, 4340 modified, Grade 300 Maraging Steel, Ti-6Al-6V-2Sn, Ti-6Al-2Sn-4Zr-2Mo, Inconel 718, AF95, Rene' 80 and AF2-1DA. For the most part, these alloys were quenched and tempered or solution treated and aged, as appropriate, to put them into a high strength structural condition.

Wide variations in fatigue strength were documented for the above mentioned alloys under the following metal removal conditions: surface grinding, hand sanding, end milling-peripheral cutting, end milling-end cutting, EDM and ECM.

Guidelines for processing of aerospace hardware in such a way as to assure good surface integrity have been developed and presented in this report. Control of cutting tool sharpness as well as proper selection of processing parameters are prime requirements.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Surface integrity						
Surface damage						
Surface alterations						
Machining						
Surface grinding						
Hand sanding						
ECM						
EDM						
Fatigue						
Residual Stress						
AISI 4340						
4340 Modified						
Grade 300 Maraging Steel						
Ti-6Al-4V						
Ti-6Al-6V-2Sn						
Ti-6Al-2Sn-4Zr-2Mo						
Inconel 718						
AF95						
Rene' 80						
AF2-1DA						